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Working with WhAEM2000

Source Water Assessment for a Glacial Outwash Wellfield, Vincennes, Indiana

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Working with W*h*AEM 2000
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Notice

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Abstract

This purpose of this document is to introduce the use of the ground water geohydrology computer program W*h*AEM for Windows 95/98/NT, or W*h*AEM2000. W*h*AEM2000 is a public domain, ground-water flow model designed to facilitate capture zone delineation and protection area mapping in support of the State's Wellhead Protection Programs (WHPP) and Source Water Assessment Planning (SWAP) for public water supplies in the United States. Program operation and modeling practice is covered in a series of progressively more complex representations of the wellfield tapping a glacial outwash aquifer for the city of Vincennes, Indiana. W*h*AEM2000 provides an interactive computer environment for design of protection areas based on radius methods, well in uniform flow solutions, and geohydrologic modeling methods. Protection areas are designed and overlaid upon US Geological Survey Digital Line Graph (DLG) or other electronic base maps. Base maps for a project can be selected from a graphical index map for the State. Geohydrologic modeling for steady pumping wells, including the influence of hydrological boundaries, such as rivers, recharge, and no-flow contacts, is accomplished using the analytic element method. W*h*AEM has on-line help and tutorials.

Foreword

The National Exposure Research Laboratory's Ecosystems Research Division (ERD) in Athens, Georgia, conducts research on organic and inorganic chemicals, greenhouse gas biogeochemical cycles, and land use perturbations that create direct and indirect, chemical and non-chemical stresses, exposures, and potential risks to humans and ecosystems. ERD develops, tests, applies, and provides technical support for exposure and ecosystem response models used for assessing and managing risks to humans and ecosystems, within a watershed/regional context.

The Regulatory Support Branch (RSB) conducts applied research and development, and provides technical support and assistance to customer Program and Regional Offices, States, Municipalities, and Tribes. As an outreach for ERD research on the occurrence, movement, transformation, impact, and control of environmental contaminants, RSB develops management and engineering tools to help environmental resource managers achieve environmental goals through comprehensive watershed management. Exposure models are distributed and supported via the EPA Center for Exposure Assessment Modeling (CEAM).

The development and release of the Wellhead Analytic Element Model (W*h*AEM2000) is in support of the State's and Tribe's Source Water Assessment and Wellhead Protection Programs as required by the Safe Drinking Water Act. W*h*AEM2000 is a general purpose ground water hydrology tool based on the innovative modeling technique known as the analytic element method and a standard Windows graphical user interface. W*h*AEM2000 assists in the delineation of the area contributing source water to public water supply wells. The development of W*h*AEM2000 has been a cooperative effort between the Office of Research and Development and the Office of Ground Water and Drinking Water.

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Chapter 1

BACKGROUND

The objective of this document is to introduce the geohydrology computer model W*h*AEM2000. The presentation will cover both basic model operations and modeling practice. We will use a source water area assessment associated with the wellfield of the city of Vincennes, Indiana, to emphasize a step-wise and progressive modeling strategy.

1.1 Source Water Protection Programs

Ground water is a valued source of public drinking water in many parts of the country. Not only is the ground water resource renewable if properly managed, its quality can be excellent, due to the natural cleansing capabilities of biologically active soil cover and aquifer media. It has come to the public attention in the past few decades that ground water wells can be threatened by over-drafting and pollution. Source water protection is based on the idea of protecting public water wells from contamination up front, and working to maintain the quality of the resource. Source water protection means taking positive steps to manage potential sources of contaminants and doing contingency planning for the future by determining alternate sources of drinking water. The Safe Drinking Water Act has required the USEPA to develop a number of programs that involve the source water protection concept for implementation at the State level, such as the Wellhead Protection Program and the Source Water Assessment Program [USEPA,1999].

In its essence, the source water protection process involves the assessment of the area contributing water to the well or wellfield, a survey of potential contaminant sources within this area, and an evaluation of the susceptibility of the well to these contaminants. This includes the probability of contaminant release and the probability of transport through the soil and aquifer to the well screen.

The designation of the wellhead protection areas is then a commitment by the community to source area management. Delineation of the wellhead protection area is often a compromise between scientific and technical understanding of the geohydrology and contaminant transport, and practical implementation for public safety.

The USEPA Office of Ground Water and Drinking Water established guidance on the criteria and methods for delineating protection areas [USEPA,1993], [USEPA,1994]. The criteria include: (1) distance; (2) drawdown; (3) residence time; (4) flow boundaries; and (5) assimilative capacity. The methods applying the criteria range from the simple to the complex, including setback mapping, calculated radius, and geohydrologic modeling (see Table 1.1). This document will review the distance, residence time, and geohydrologic modeling criteria and their methods using W*h*AEM using the Vincennes, IN case study. The evaluation of assimilative capability is an active area of research and will not be a focus in this document.

Table 1.1: **Wellhead protection area delineation criteria and methods.**

>>>>METHODS CRITERIA	arbitrary fixed radius	calculated fixed radius	well in uniform flow field	geo-hydro-logic mapping	geo-hydrologic modeling	transport/ transfor-mation modeling
distance	x	x				
drawdown		x	x		x	
residence time		x	x		x	x
geohydrologic boundaries				x	x	x
assimilative capability						x

1.2 Modeling Philosophy

The philosophy presented below is for mathematical deterministic modeling, and a more complete discussion can be found in [Konikow and Bredehoeft, 1992]. The reader is also encouraged to explore an alternative modeling approach based on stochastic theory [Leeuwen et al., 1998], [Vassolo et al., 1998].

Modeling of flow and transport through geohydrologic systems is a complex undertaking. Our definition of good modeling practice revolves around step-wise problem solving. The mathematical model is an abstraction of the real world, and all abstractions are simplifications. The challenge is to make the abstraction represent the essence of the natural system as required by the problem at hand. Representation of the advective flow system is understood to be prerequisite to modeling transport and transformations.

Formally speaking, mathematical modeling of ground-water flow is concerned with finding solutions to a governing differential equation subject to a set of boundary conditions. This procedure can be simple or complex depending on the ground-water flow processes included in the differential equation and the complexity of the boundary conditions. That combination of processes and boundary conditions is referred to as the "conceptual model". An example of a very simple conceptual model is a single well in a homogeneous confined aquifer near a straight infinitely long "equipotential" (line of constant head). Such a conceptual model is a severe abstraction of a well near a stream or lake boundary. The actual meandering surface water boundary is replaced by an infinitely long straight line, heads underneath it are assumed equal to the surface water elevation, aquifer properties are assumed uniform and homogeneous throughout the flow domain, and lastly the ground-water flow is assumed to be purely horizontal. The virtue of this conceptual model is the ease with which a solution can be obtained (Thiem's solution for a well with an image recharge well across from the equipotential line). Of course, the price paid is the lack of realism of this conceptual model when compared to the complex reality of a partially penetrating well near a meandering stream with a silty stream bottom in a heterogeneous aquifer of varying thickness.

A realistic conceptual model is often thought of as a representation of reality that includes most if not all of the geologic and hydrologic complexities of an aquifer or aquifer system. The more realistic (read complex) a conceptual model is the more involved the modeling becomes, mostly for the following two reasons:

1. Field data requirements may escalate when striving for maximum realism.

2. Computer codes needed to solve complex conceptual models are difficult to operate.

While incorporation of more and more "realism" in the conceptual model may suggest an increasingly accurate representation of the ground-water flow regime, the *reality* may well be different. Increased data requirements and the associated data uncertainty, as well as the difficulty to interpret the results of complex (multi-parameter models) can defeat the theoretical improvement in model realism. This is not only true for ground-water flow modeling. Albert Einstein is known to have offered the following advice when talking about models of the universe: "Build your models as simple as possible, but not simpler". In other words, good modeling practice requires a balance between the realism of the conceptual model and the practical constraint of parameterizing the resulting ground-water flow model.

When deciding on an appropriate conceptual model it is important to not only take the complexity of the geohydrology into account, but also the objective of the modeling exercise. In the context of wellhead protection the purpose of the modeling is the delineation of a "time of travel capture zone" for one or more drinking water production wells. The delineation of the time of travel capture zone, for the purpose of wellhead protection, is based on the assumption of steady state ground-water flow and average ground water travel times. A time of travel capture zone, defined in this manner, is arguably not the most relevant entity when it comes to protecting drinking water wells from potential toxic substances. The movement of contaminants toward a drinking water well is a complex contaminant transport problem where such processes as dispersion, adsorption and (bio)chemical reactions strongly influence the degree to which a well is actually exposed to contaminants in the aquifer. Incorporation of all these aspects in the definition of a wellhead protection zone would require sophisticated transport modeling for a whole series of different contaminants. The field data requirements for such an endeavor are staggering, while the technology to reliably describe these contaminant transport processes is not completely developed. In any case, the definition of multiple wellhead protection areas, one for each potential contaminant, is impractical to say the least. Consequently, many States base their wellhead protection areas on time of travel capture zones that result from considering average ground water travel times and steady state (average) flow conditions.

The essence of good ground-water flow modeling is to find a proper balance between a simple conceptual model and a realistic one. The most economical way to judge whether or not a conceptual model is not too simple, is to gradually increase its complexity and investigate the effect on the purpose of the modeling; the time of travel capture zone in this case. A very good example is the classical dilemma of modeling two-dimensional flow or three-dimensional flow. Most modelers feel inadequate when using a horizontal flow model (based on the Dupuit assumption), when realizing that the actual world is clearly three-dimensional. Intuition, however, offers poor guidance here. Only a comparison between a three-dimensional solution and two-dimensional one can answer this question. This is true for all aspects of conceptual model design. The need to include aquifer heterogeneities, varying recharge rates, resistance to flow in or out of surface water features, etc. can only be assessed by comparing ground-water flow solutions with and without these features. In all cases it is important to look at the impact on the time of travel capture zone, since that is what we are modeling for. Once progressively more complex conceptual models do not change the time of travel capture zone in a meaningful way, the modeling may be considered complete. Sometimes, it may be preferable to trade data acquisition and model complexity for a larger, thus more protective, wellhead protection zone. Such a conservative time of travel capture zone may be obtained by making some assumptions that are known to lead to a larger capture zone than the one that may result from a more detailed conceptual model.

Fortunately, we do not always have to repeat the procedure of hypothesis testing with increasingly complex conceptual models for each individual modeling project. After a while some general conclusions may be drawn from comparing simple and complex conceptual models. In many cases the validity of certain assumptions have already been investigated by others and are published in the literature. It is not practical to present here a complete list of valid and invalid conceptual models, covering all possible geohydrological circumstances. It is the responsibility of the modeler to refer to the ground water literature and make these choices on a case by case basis. We will, however, provide a few general rules of thumb that may be of help in making some initial decisions regarding conceptual models.

1.2.1 Rules of thumb

1. **Multi-Aquifer Flow.** The subsurface is usually stratified (layered) with each layer having its own hydraulic conductivity. If the hydraulic conductivities of the various formations are all within the same order of magnitude, the formations form one *stratified* aquifer, see item 4 in this list. If on the other hand one or more layers have a hydraulic conductivity that is more than an order of magnitude lower than the more permeable layers they are

referred to as aquitards. Aquitards divide the subsurface into more than one aquifer, forming multi-aquifer systems. In case of a multi-aquifer system a multi-aquifer model (quasi three-dimensional model) may be necessary if all of the following circumstances apply:

(a) The well occurs in a multi-aquifer zone and is not screened in all aquifers.

(b) The length of the capture zone, based on flow in the aquifer(s) accessed by the well, is in the order of (or smaller) than $4\sqrt{Tc}$, where T (ft^2/day) is the transmissivity of the aquifer and c $(days)$ is the largest resistance of one of the adjacent aquitards.

(c) A hydrological boundary (stream or lake)is present within a distance of $4\sqrt{Tc}$ from the well, where T (ft^2/day) is the transmissivity of the aquifer and c $(days)$ is the largest resistance of one of the adjacent aquitards.

Multi-aquifer flow often greatly complicates the delineation process due to uncertainties in aquifer interaction. In many cases, aquifers do not interact through a homogeneous leaky aquitard, but through discrete openings in clay layers, whose presence and location may or may not be known. If a well is screened in only one aquifer, the largest time of travel capture zone will occur if interaction with adjacent aquifers is ignored. If the direction of flow in the various aquifers are expected to be not too different, the single aquifer capture zone may offer a conservative time of travel capture zone.

2. **Three-Dimensional Flow.** Three-dimensional flow modeling may be necessary when one of the following circumstances apply:

(a) The well or well field is within a distance of $2\sqrt{k_h/k_v}H$ from a hydrological boundary, where k_h and k_v are the horizontal and vertical hydraulic conductivity, respectively, and where H is the average saturated aquifer thickness.

(b) The width of the capture zone in a two-dimensional model is less than $2\sqrt{k_h/k_v}H$, where k_h and k_v are the horizontal and vertical hydraulic conductivity, respectively, and where H is the average saturated aquifer thickness.

Note that in the event that the (2D) capture zone width is in the same order than the aquifer thickness, the three-dimensional capture zone is likely a slender three-dimensional stream tube that may occur at some depth below the water table. A conservative (protective) time of travel capture zone may be obtained by using a wellhead protection zone that is obtained from a horizontal flow model with a confined aquifer of the same thickness as the length of the well screen.

3. **Aquifer Heterogeneities.** Small inclusions of clay or gravel with different hydraulic conductivities than the average regional value are inconsequential, except if their size is on the order of the capture zone width or larger.

4. **Aquifer Stratification.** An aquifer is considered stratified if the hydraulic conductivities of the various geological formations (layers) are within the same order of magnitude. Aquifer stratification will not affect the capture zone width, but may significantly affect the capture zone length. The groundwater flow velocities in the various aquifer layers are proportional to their hydraulic conductivity and inversely proportional to their porosity. This can lead to substantially different time of travel capture zone lengths in the various layers. If it is considered important to include this in the definition of a wellhead protection zone, a time of travel capture zone may be produced using a porosity value for the aquifer that incorporates both the effect of the highest conductivity and the associated porosity. For instance, for an aquifer layer with five times the average hydraulic conductivity the model should be given a porosity that is five times smaller than the average porosity in order to get the correct time of travel capture zone length in that layer. This is assuming that the porosity is the same in all layers.

5. **Transient Flow.** Highly permeable unconfined aquifers, and most confined aquifers, will exhibit "summer conditions" and "winter conditions" that may be approximated by steady-state solutions using recharge rates and

surface water levels observed in the summer and winter, respectively. When delineating capture zones for wells based on residence times greater than say 5 years, the detailed day-to-day pumping records can safely be averaged over the observation period. However, accurate delineation for transient non-community wells may require special attention. And projections into the future should include additional safety factors.

1.3 The Role of W*h*AEM

Nearly all ground water modeling projects are constrained by a finite budget and a finite amount of time. This is particularly true for time of travel capture zone delineation in the context of wellhead protection. Most States are confronted with the task of developing wellhead protection programs for thousands of public drinking water supply systems in only a few years time. Conducting an extensive ground water modeling campaign for each individual drinking water well (or well field) is out the question, both in view of the time involved and the cost. The USEPA recognized this reality from the start and proposed a series of simplified capture zone delineation methods to facilitate a timely implementation of the States wellhead protection programs:

1. arbitrary fixed radius method.
2. calculated fixed radius method.
3. well in a uniform flow method.
4. geologic mapping.
5. ground-water flow modeling based on a simple conceptual model.
6. ground-water flow modeling based on a sophisticated conceptual model.

While only the latter, all-out modeling exercise may completely satisfy the groundwater hydrologist, the more approximate approaches are offered to get the job done. The rationale behind this policy is that it is better to define a less then perfect wellhead protection zone than none at all. The task of the ground water hydrologist is to select the best possible approach within the time and budget constraint of the wellhead protection program. The first two methods lead to circular wellhead protection zones and often over-protect some areas and not protect other areas near the well. The third method takes ambient ground-water flow into account (approximately) and offers a significantly better approximation of the actual time of travel capture zone. That approach has been implemented in a computer code WHPA, made public by the USEPA [Blanford and Huyakorn,1993]. WHPA also allows for the approximate incorporation of a stream or lake boundary, a low permeable geologic boundary, or both.

W*h*AEM2000 (pronounced wăm) offers a next step. It allows the incorporation of the principal hydrologic boundaries (surface waters) in the regional ground-water flow domain and calculates ambient ground-water flow patterns based on aquifer recharge due to precipitation in the presence of these surface waters. Consequently, the ambient flow does not have to be specified a priori and will not be limited to a uniform flow field. Also, surface water features and geologic boundaries are not limited to infinitely long straight lines (WHPA), but can be of arbitrary shape, further improving the realism of the conceptual model. On the other hand, W*h*AEM2000 lacks areas of differing hydraulic conductivity, varying aquifer bottom elevations, resistance to flow in or out of surface waters, multi-aquifer flow, etc., which are supported in full-feature ground water models. This limits the applicability of W*h*AEM2000, but also makes the code easier to operate and thus easier to learn. In addition, the relatively simple conceptual model of W*h*AEM2000 requires less input data, thus further simplifying its use. Taken together, time of travel capture zone delineation with W*h*AEM2000 is considerably cheaper than when using a full feature ground water flow model such as e.g. MODFLOW. Obviously, the price for this is a less sophisticated (potentially less accurate) definition of the time of travel capture zone. W*h*AEM2000 clearly offers more realism than the first three approaches in the list, but also requires more work (more time and more money). In some cases this may be justified, in some cases one of the simpler methods may be adequate, and in some other cases a more powerful ground water model must be employed. It is the responsibility of the hydrologist to determine whether or not W*h*AEM2000 is an adequate tool for the delineation of a time of travel capture zone for a particular public water supply system. That decision, as explained, should be based on technical merits, while taking into account the practical limitations associated with the timely implementation of the entire wellhead protection program.

1.3.1 Evolution of W*h*AEM

The USEPA has been working on general purpose source water delineation computer models for a number of years. The release of the WHPA model came in the early 1990s [Blanford and Huyakorn,1993]. WHPA offers a number of ground water flow solutions, including the well in uniform flow, and wells in flow fields generated by enclosed (rectangular) boundaries. WHPA uses particle tracking to draw bundles of streamlines toward the well, including the boundary streamlines that define the capture zone for the well. By drawing streamlines with a constant ground water residence time, from starting point to the well, a *time-of-travel* capture zone is delineated. WHPA is menu driven, has a windows-like graphical user interface under DOS, and requires minimal computer resources.

The release of CZAEM [Strack et al.,1994] introduced a new analytical solution technique to the wellhead community – the analytic element method. This method is based on the principle of superposition of many closed-form analytic functions, each representing a hydrological feature, such as point-sinks for wells, line-sinks for rivers, area elements for zones of effective recharge, line doublets (double layers) for geologic contacts [Strack,1989], [Haitjema,1995]. The two-dimensional analytic element models invoke the Dupuit assumption, that is, that resistance to vertical flow is negligible and that the head is constant with depth (zero vertical head gradients). This Dupuit assumption is reasonable when the capture zone is an order of magnitude wider than the saturated thickness of the aquifer. The significance of the Dupuit assumption is to approximate a three-dimensional flow field by a two-dimensional one. Implementation of the analytic element method in CZAEM includes wells, line-sinks, uniform flow, and circular recharge elements, and is operated from a DOS command line. CZAEM has sophisticated routines for drawing time-of-travel based capture zone envelopes and time and source water sub-zones [Bakker and Strack,1996].

A graphical user interface (GUI) and geographic preprocessor was added to CZAEM in the first release of W*h*AEM [Haitjema et. al, 1995], [Haitjema et. al, 1994]. W*h*AEM2000 includes a full windows graphical user interface, the use of U.S. Geological Survey (USGS) digital line graphs (DLGs) as the base map, a new solution engine ModAEM [Kelson,1998] that includes arbitrarily shaped no-flow boundaries. W*h*AEM2000 supports delineation by fixed radius, calculated radius, well in uniform flow, and steady flow in confined/unconfined aquifers with constant aquifer properties and recharge. W*h*AEM2000 runs under Windows 95/98/NT.

1.4 The Base Map

Ground-water models are applied to regular Cartesian coordinate systems, even though the surface of the Earth is curved. Cartographers have solved the problem by projecting the surface of a spheroid, where position is measured in latitude and longitude, to a rectangular coordinate system on a flat piece of paper. In addition, we need to define the origin of our ground-water model coordinate system in a standard way so that we can overlap maps and spatial data from different sources.

W*h*AEM can use any Cartesian coordinate system, including universal transverse mercator (UTM), State Plane, local site coordinates, etc. The graphical user interface (GUI) for W*h*AEM provides both pre- and post- processing in the base map coordinates, while the computational engine ModAEM [Kelson,1998] operates in local rectangular coordinates for reasons of numerical accuracy, but this is hidden from the user.

We will build our base maps for the modeling exercises described in this document using the USGS Digital Line Graph. DLG maps include lines for hydrography (rivers, lakes, etc), roads, topography, and other line features. DLG

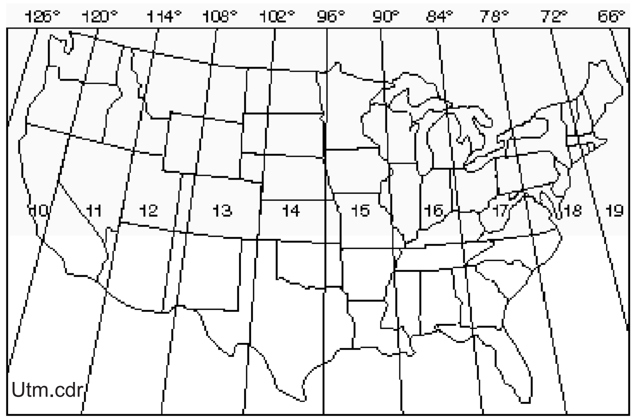


Figure 1.1: UTM zones of the conterminous U.S.

maps are available at convenient scales for ground water modeling, including the intermediate scale (1:100,000) and the large scale (1:24,000). DLG maps are available for download on the web (See Appendix B).

The DLG maps use the UTM projection [USGS,1997]. In this grid system, the globe is divided into 60 north-south zones, each covering a strip 6 degrees wide in longitude. The zones are numbered from 1 to 60, where by zones 10 to 19 cover the conterminous U.S. Figure 1.1. In each zone, coordinates are measured north and east in meters. The northing values are measured continuously from zero at the Equator, in a northerly direction. A central meridian through the middle of each 6 degree zone is assigned an easting value of 500,000 meters. Grid values to the west of this central meridian are less than 500,000 meters; to the east they are more than 500,000 meters. (Caution: Base maps do not smoothly join across UTM zones!)

For performance reasons, W*h*AEM uses a compressed binary form of the DLG called BBM (binary base map). W*h*AEM reads BBM files from the disk each time it redraws a map on the screen. W*h*AEM has **Tools** to convert DLG to BBM. The W*h*AEM **Tools** also includes a State graphical basemap index file for copying BBMs to your project directory, as will demonstrated in Chapter 2. Contact the author for information regarding binary base maps for your State.

1.5 Exercise: Exploring the USGS quad map Vincennes, Indiana

We will use a source water area delineation for the well field of Vincennes, Indiana, as a case study throughout this document. The case study will be used to: (1) familiarize the reader with the basic operations of W*h*AEM ; and (2) illustrate some basic ground-water modeling concepts.

Vincennes is home to about 20,000 people, is the seat of Knox County, and is located in the alluvial flood plain of the Wabash River in the southwestern quadrant of Indiana. See Figure 1.2. The floodplain of the Wabash River is characterized by valley fill from glacial outwash, and consists of coarse sand and fine gravel on top of underlying bedrock. The area receives about 40 inches per year of precipitation. The areal recharge to the aquifer is estimated to be 12.1 inches per year, and the average hydraulic conductivity of the local aquifer is 350 feet per day, and an effective porosity is 0.2 [Shedlock, 1980]. The wellfield pumped about 2.75 MGD (million gallons per day) in 1977, and about 3.5 MGD in 1999. We will explore more details about the wellfield throughout this document.

In this exercise, we will place the Vincennes wellfield in its geographic context. You will locate the wellfield on the digital U.S. Geological Survey 7.5 minute topographic map (vincenne.tif) using the DLG-Viewer [USGS,1998]. The DLGV32 program is available for download from the USGS webpage (http://mcmcweb.er.usgs.gov/drg/). The digital raster graphic (DRG) file (vincenne.tif) is supplied on CD-ROM during the W*h*AEM2000 training course, or can be

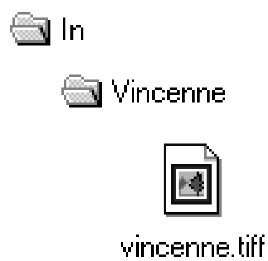
Figure 1.2: Location of Vincennes, Indiana

purchased from the USGS. Alternatively, you can purchase and work with the paper copy of the quad map.

We will assume basic familiarity with the Microsoft Windows operating system, and basic mouse operation.

Step 1 Start the USGS DLG-View program and open the file `vincenne.tif`.

How? From Windows, use the mouse to **Start**, **Programs**, **US Geological Survey**,**dlgv32**. From the Menu bar, click on **File**, **Open as New**, and look in CD-ROM drive folders for the `vincenne.tif` file, select **File as Type** GeoTIFF(DRG,DOQ,DEM)(*.tif,*.tiff, *.drg, ...), select **File Name** `vincenne.tif`, and **Open**.



Size your view to fill the monitor screen. Figure 1.3.

Step 2 Test out the Smart Icons buttons: **Zoom In, Zoom Out, Full View, Zoom Tool, Pan**.

How? You will use the smart icons (see Figure 1.4) of the USGS DLG-View program to reposition the view.

Zoom In to the City of Vincennes, and find the city wellfield, Figure 1.5. Note the UTM coordinates of the pumping center reported in the Status Message bar in the lower right corner of the Workspace (452650 m, 4280665 m). **Pan** up the Wabash River to the north and locate where the 400 foot topographic line crosses the river.

Minimize the view to continue to the next chapter, or exit the program by clicking **File** and **Exit**.

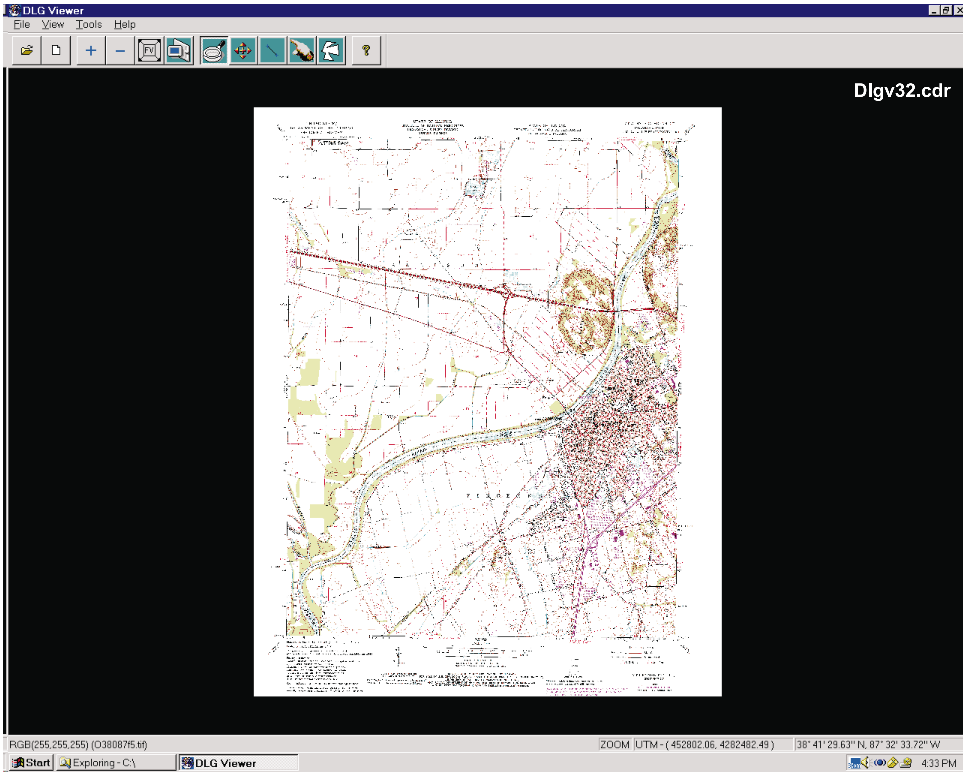


Figure 1.3: USGS DLG-View of Vincennes, Indiana.

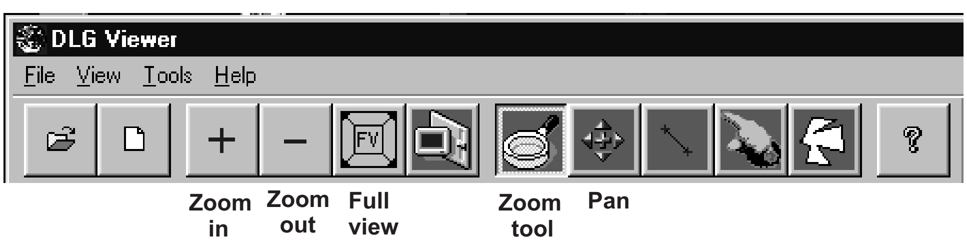


Figure 1.4: USGS DLG-View icons.

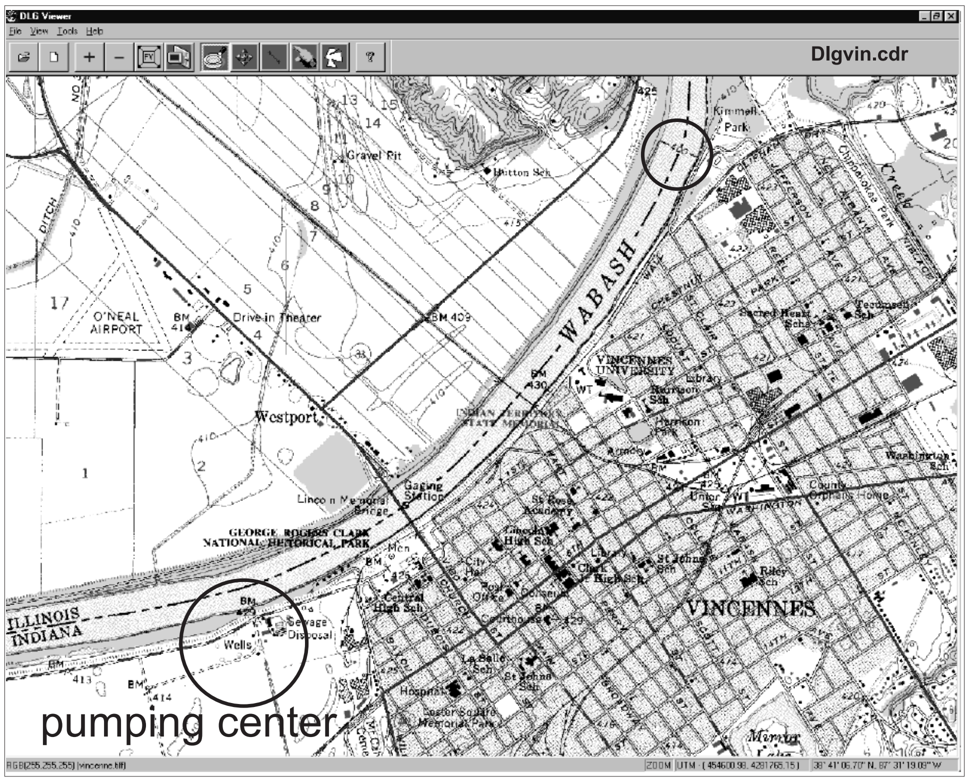


Figure 1.5: Zoom in view of Vincennes wellfield.

Chapter 2

PROTECTION ZONES I – DISTANCE CRITERIA

2.1 Setbacks

One of the basic criteria for defining a protection zone surrounding a pumping well or wellfield is distance. The method of designating a setback based on a fixed radius is commonly used by the States [Merkle et al.,1996]. For example, Indiana promotes a setback distance of 200 feet between potential sources and public drinking water wells. The fixed radius is the first line of defense against surface contaminants that could reach the wellhead and travel down an improperly sealed borehole into the ground water near the well. A fixed radius wellhead protection zone is also used as a setback for potential sources of microbial pathogens. The assumption is that pathogens that enter the ground water outside the setback area will become inactive before entering the well. The actual survival time of pathogens in ground water, however, is still the topic of ongoing research. And the setback is not likely protective from a gasoline spill which includes the additive MTBE (methy tertiary butyl ether) which resists assimilation in many subsurface environments.

2.2 Exercise: Vincennes, Indiana

$\boxed{\text{Step 1}}$ Start W*h*AEM and familiarize yourself with the graphical user interface (GUI).

From the **Start** button, go to **Programs**, and start **W*h*AEM** for Windows. The "About W*h*AEM for Windows" screen will appear, and credits are given. Figure 2.1. Click to start W*h*AEM and the Welcome page appears. You are welcome to do the on-line tutorial,but for now, click to "start W*h*AEM ". Figure 2.2.

The workspace for W*h*AEM has standard windows features: a Menu bar on top; smart icons bar underneath the menu bar; status bar on the bottom of the window. Figure 2.3.

$\boxed{\text{Step 2}}$ Import the Vincennes base maps using the Base map browser.

From the Menu bar, drop down the **Tools** options.

Note: You can use keyboard short cuts by using the key combination `ALT` plus the underlined character of the command, such as `ALT + T`.

Choose W*h*AEM Base map Browser. In the window "Load Map Browser Index File" select your drive, open the folder for Indiana Maps, and select the binary map index file **IN.bmi** (See Figure 2.4). Click on the Vincennes (30 x 60 minute) map area. Figure 2.5. Now click on the 15 x 15 minute area for the Vincennes quad. Choose your target

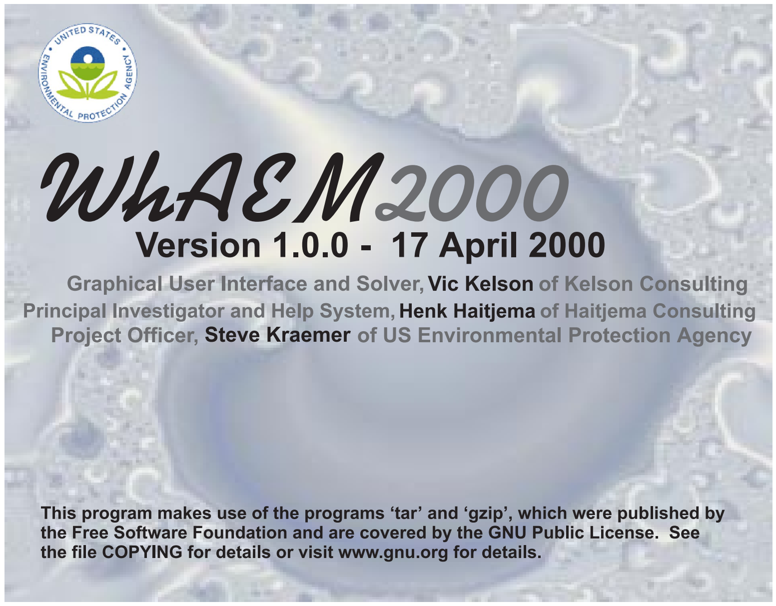


Figure 2.1: W*h*AEM splash screen.

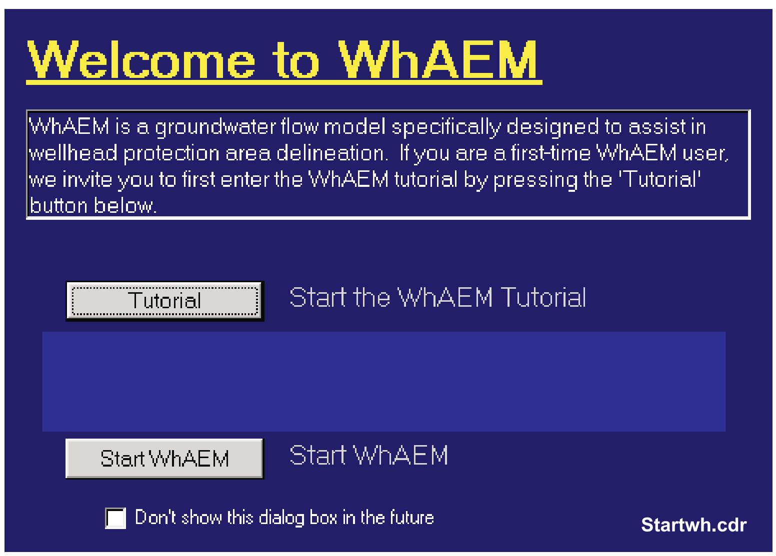


Figure 2.2: Start W*h*AEM .

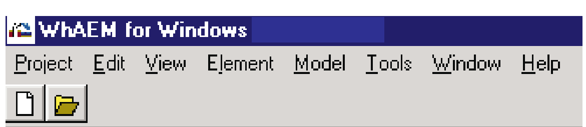


Figure 2.3: W*h*AEM menu bar.

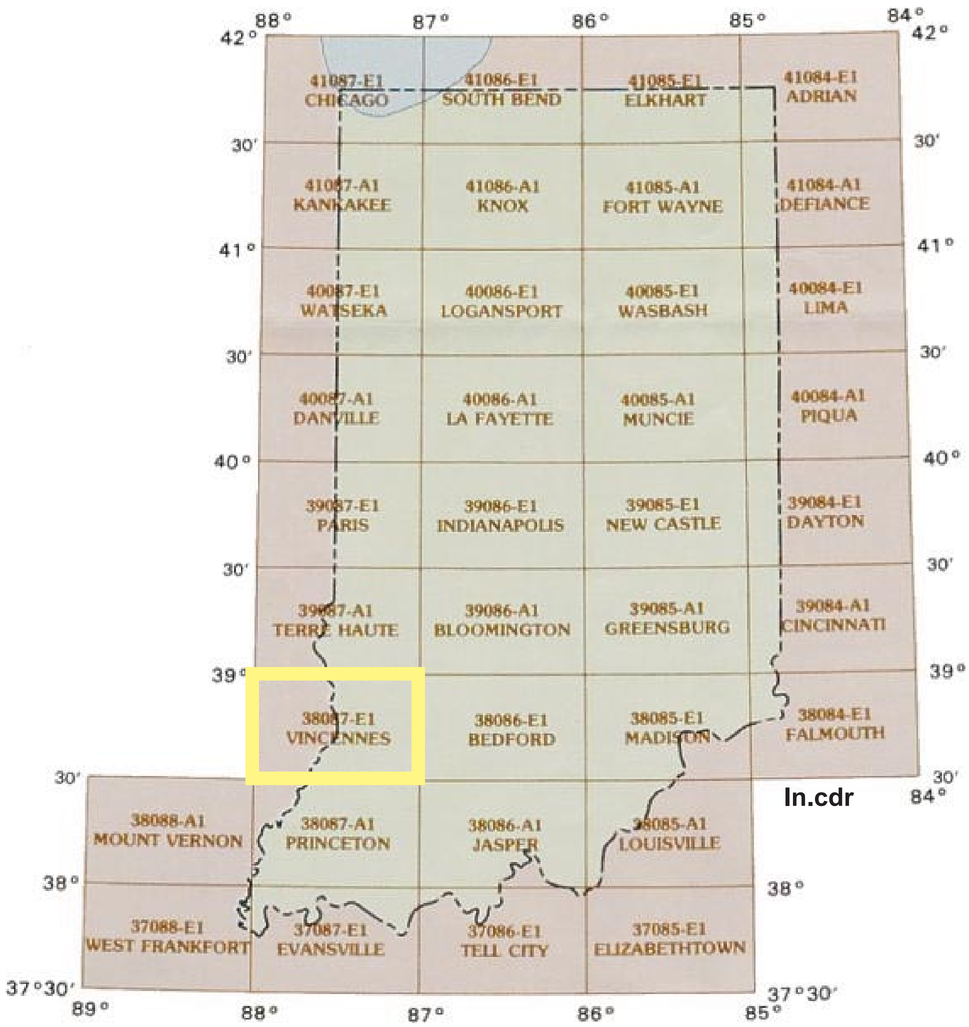


Figure 2.4: View of Indiana binary map index. The boundary of the Vincennes 30 x 60 minute map is highlighted.

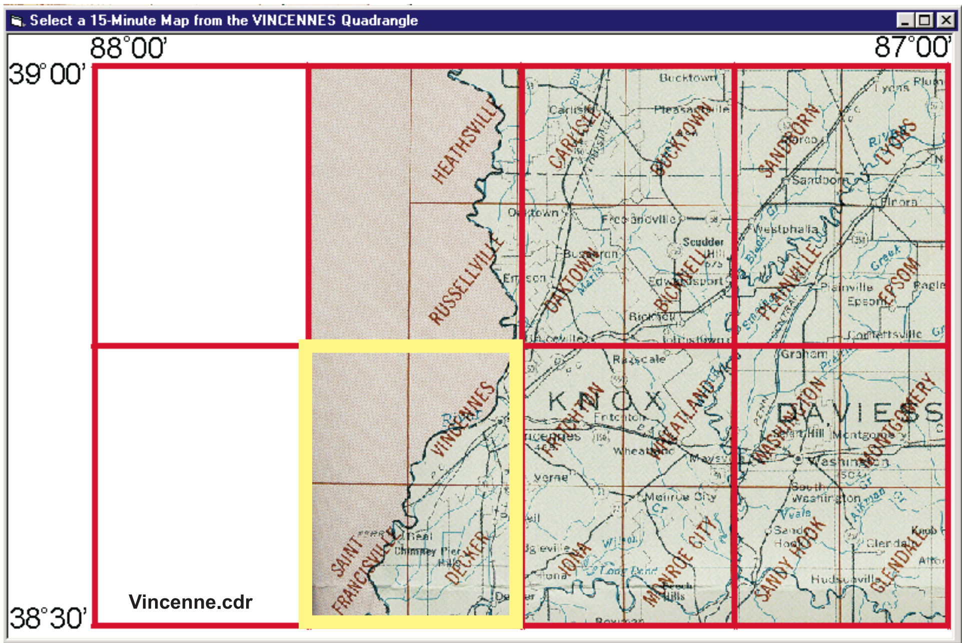
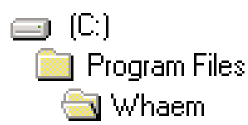


Figure 2.5: View of the 30 x 60 minute for Vincenne quad. The Vincennes 15 x 15 minute area is highlighted.

directory by clicking on the folder icon and on the folders in the window.

Note: do not change the name "target" in the Filename box!

It is suggested you select folder (assuming C: represents your installation drive)



as your target. Click **Open**. Confirm the transfer of the binary base maps (bbm) to your target directory, e.g. respond **Yes** to vi1hyf06.bbm, vi1rdf06.bbm, vi1rrf06.bbm, vi1mtf06.bbm transfer. Close both map selection windows by clicking the $\boxed{x}$ in the upper right corner of each Window.

From the Menu Bar, drop down the **Project** options. Select **New Database**, and select your project folder (Program Files, WhAEM) on the hard drive, and type `vinbase` into the dialog box for the file. Click **Open**.

The "New Database Wizard" will prompt you for a project description and the units associated with the input data. W*h*AEM requires consistent units, either meters and days or feet and days. Select **meters** for the "Distance Units in Basemaps Files", because the binary base maps provided are in UTM coordinates). Select **feet and days** as the "Units for Computations". After you made these selections by clicking on the proper radial buttons click on **Create Database**.

Note: If you get an error message that W*h*AEM cannot open the database, you may have forgotten to select a directory on the hard drive and W*h*AEM is trying to write to the CD-ROM drive. Redo the procedure by opening the Project menu again.

Note: Your base map units are actually not a choice, but are dictated by the units of your electronic source. The coordinates displayed on-screen will match your map units. The units for computation are your choice. For instance, if you select feet and days for your units for computations, the hydraulic conductivity must be entered in feet per day and a well pumping rate must be entered in cubic feet per day. The GUI will convert the base map units to the computational units when forwarding data to the solver, which works in consistent units.

The next window facilitates the definition of base maps (in binary format). The window "Currently Used Base maps"

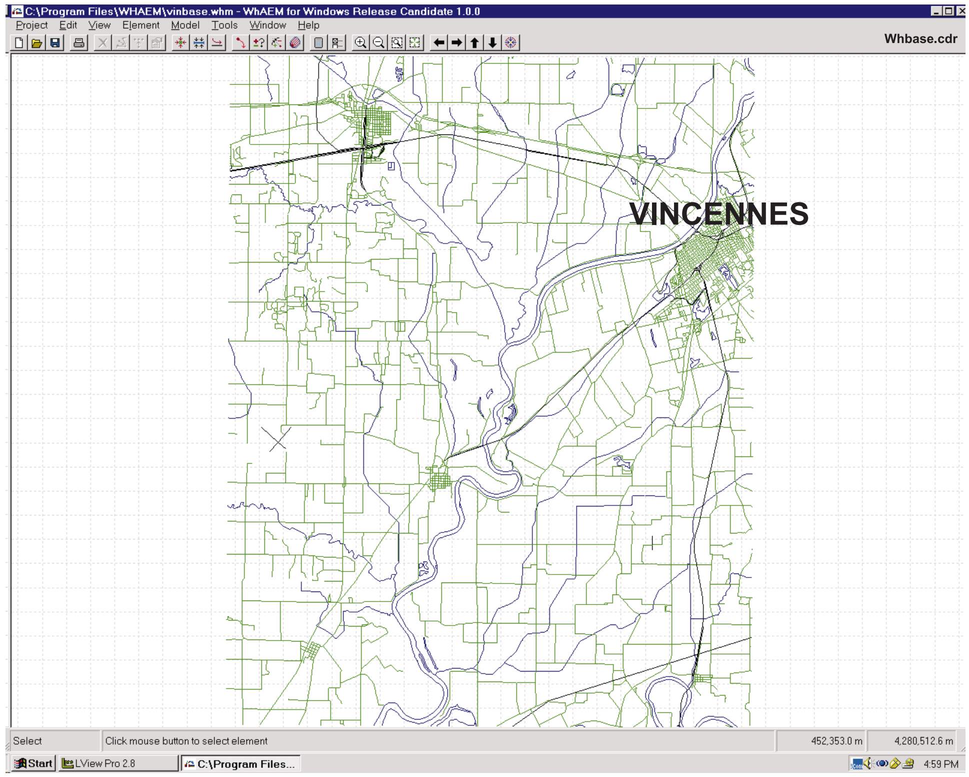


Figure 2.6: The base map view.

will be empty at this point. Click on **Add BBM** to display the available *.bbm files. Click on the file *vi1hyf06.bbm*, and click on **Open**. Repeat this procedure to add the file *vi1mtf.bbm*, *vi1rdf06.bbm*, and *vi1rrf06.bbm*. All four bbm files of the base map should be displayed in the box "Currently Used Basemaps". Now click **OK**. The maps will be loaded and plotted in the graphics box. Figure 2.6. See Appendix B for information about the USGS naming convention for these files.

Super-imposed on the map is a so-called editor grid. You may turn this off by clicking on the **View** menu, then **Base Map**, and deselect **Show Editor Grid**.

From the Menu Bar, drop down the **View** options. Go to Basemap to view the available layers: *vi1hyf06* (streams); *vi1mtf06* (misc); *vi1rdf06* (roads); *vi1rrf06* (railroads). Play with toggling these layers on and off and observe the change in the view.

From the smart icons bar, test the zoom in, zoom out, zoom to extents, zoom to window icons, scrolling, and re-centering. Figure 2.7.

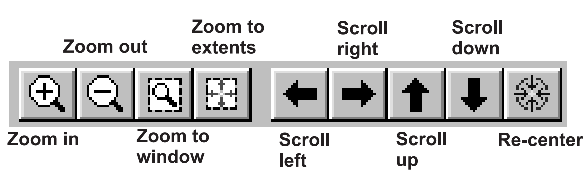


Figure 2.7: The View smart icons.

Step 3 In this step you will locate a well in the center of the Vincennes wellfield, and draw setback protection area.

Save this part of the project as "setback1". (**Project** , **Save As**, `setback1`).

Minimize the W*h*AEM window. Restore (or open) the **dlgv32** program and explore the Vincennes DRG map. Zoom to the Vincennes wellfield. Position the cursor near the pumping center and read off the UTM coordinates. Note that $452650m, 4280665m$ is about the pumping center. Minimize or exit the program dlgv32.

Restore the W*h*AEM window. Zoom in to the city of Vincennes.

To create a well, from the Menu select **Element** , then select **New** and click on **Well**. Move the cursor to the approximate location of the well, based on your exploration of the Vincennes DRG map, and click the left mouse button. A marker for the location of the well is added to the base map and a dialog box appears. Type in a name, e.g. `‘‘well field’’`. Readjust the well location to be utm location $x = 452650m, y = 4280665m$ by typing into the X and Y boxes. Enter a "Setback Radius" of $200ft$. Figure 2.8.

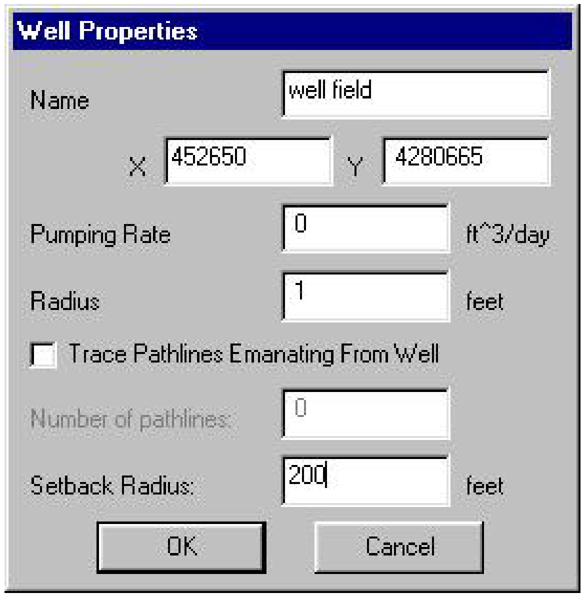


Figure 2.8: Well properties dialog box.

Click *OK* to add the well to the database.

Zoom in on the well and note the setback is plotted as a dashed circle around the well. Figure 2.9.

Draw the wellhead protection area (**Edit** , **Draw wellhead protection area**). Name the protection area "200 ft setback". With the left mouse button, click a series of short segments along the dotted outline; click with the right mouse to close the final segment.

The purpose of drawing this area by hand is to allow wellhead protection area to be different than a single realization of a capture zone. For instance, if multiple capture zones are generated using various conceptual models, a "wellhead protection area" may be drawn that envelops the various capture zones for maximum protection. Also, the draw utility allows the wellhead manager to fine tune the shape of the wellhead protection area to correspond with on-the-ground realities, such as parcel boundaries and zoning boundaries.

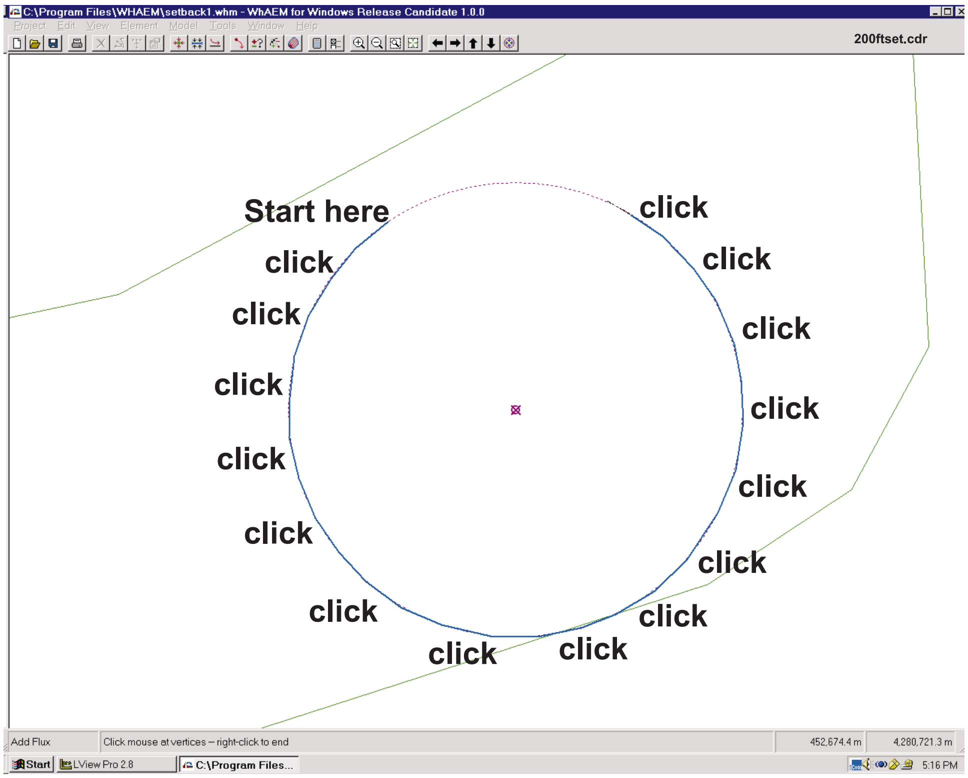


Figure 2.9: 200 foot setback.

Chapter 3

PROTECTION ZONES II — RESIDENCE TIME CRITERIA

The justification of the residence time criteria as protective of ground water source water protection is based on the assumption that: (1) non-conservative contaminants (open to sorption or transformation processes) will have an opportunity to be assimilated after a given mean time in the subsurface; or (2) that detection of conservative contaminants (no sorption or transformation) entering the protection area will give enough lead time for the drinking water community to develop a new water supply or take immediate remedial action. In this chapter we will examine two simple methods involving the residence time criteria as applied to our Vincennes case study: (1) calculated fixed radius; and (2) well in uniform flow.

3.1 Calculated Fixed Radius

The fixed radius can be calculated based on a simple two dimensional static water balance analysis, assuming negligible ambient flow in the aquifer. If we assume radial flow toward a well in an aquifer with a constant saturated thickness $H(m)$, the cylindrical boundary of radius $R(m)$ is delineated by an isochrone of residence time $t(days)$, which means that any water particle that enters the cylinder or is present in the cylinder will travel no longer than t days before being pumped up by the well (See Figure 3.1). The pumping rate of the well is $Q(m^3/day)$, the areal recharge to the water table rate due to precipitation is $N(m/day)$, and the aquifer porosity is n(-). A water balance for the period t yields:

$$N\pi R^2 t + n\pi R^2 H = Qt \tag{3.1}$$

The first term represents the inflow due to aquifer recharge, the second term represents the amount of water contained inside the cylindrical aquifer, and the term of the right hand side is the total amount of water removed by the well for the pumping period. The radius R can be expressed as:

$$R = \sqrt{\frac{Qt}{N\pi t + n\pi H}} \tag{3.2}$$

When t becomes infinitely large, the radius R represents the complete capture zone:

$$R \approx \sqrt{\frac{Q}{\pi N}} \tag{3.3}$$

Use of this equation is called the "recharge method" [USEPA,1993].

If the term $N\pi t$ becomes small, due to a small value of t or N or both, equation 3.2 reduces to:

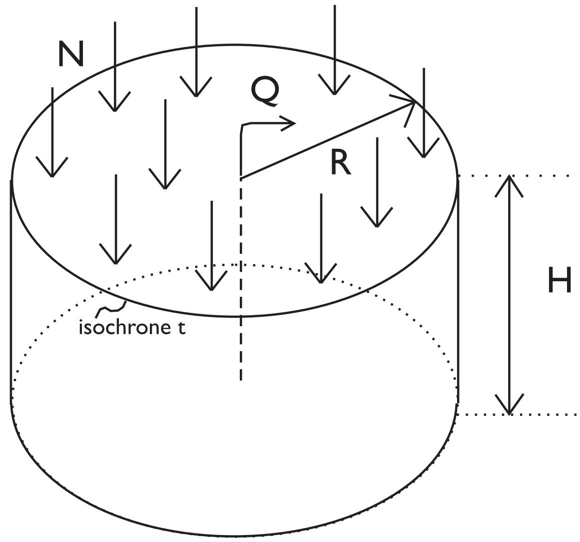


Figure 3.1: Water balance for radial flow to a well in a domain bounded by an isochrone of residence time t.

$$R \approx \sqrt{\frac{Qt}{n\pi H}} \tag{3.4}$$

Use of this equation is called the "volumetric method" [USEPA,1993].

The equations 3.2 through 3.4 only apply if the Dupuit assumption applies, that is shallow, horizontal flow. If the capture zone or isochrone radius is smaller than say twice the saturated aquifer thickness, and the well is partially penetrating, then three-dimensional effects may become important, and the approximation may lead to an underestimation of the capture zone isochrone radius R. Such a non-conservative result may be avoided by replacing the saturated thickness H in Equation 3.4 by the length of the well screen.

The radially symmetric isochrone in Figure 3.1 will only occur in the absence of ambient flow or if the well dominates the flow inside the isochrone. For an isochrone with t as 1 or 2 years and a high capacity well, the assumption of radial flow is often reasonable. However, a low capacity well in a strong ambient flow field will exhibit an elongated isochrone which extends in the upgradient direction well beyond the circular representation of that isochrone, as follows from Equation 3.2. Under these conditions the direction and magnitude of the ambient flow must be determined and isochrones should be constructed using the solution for a well in a uniform flow field.

The discussion so far assumed a constant saturated thickness H, as might occur in a confined aquifer of constant thickness. The saturated thickness of an unconfined aquifer will not be constant, even assuming a horizontal base, due to drawdown of the water table. A conservative (protective) capture zone will be obtained by using the smallest saturated thickness as H in Equation 3.4.

3.2 Exercise: Vincennes, Indiana

Step 1 Use W*h*AEM to plot the Calculated Fixed Radius protection areas based on the recharge method and the volumetric method.

We will continue to build on the `vinbase.whm` project (**Open** this project if not already). From the menu, select **Project** , then **Save as** and type `vincfr1` in the File Name box. Click **open**.

For the recharge method, use equation 3.3, and assume the well field pumps $Q = 370,000 ft^3/day$, and the areal recharge to the water table is $N = 0.00276 ft/day (12.1 in/yr)$, and calculate R. If you do not have a portable calculator

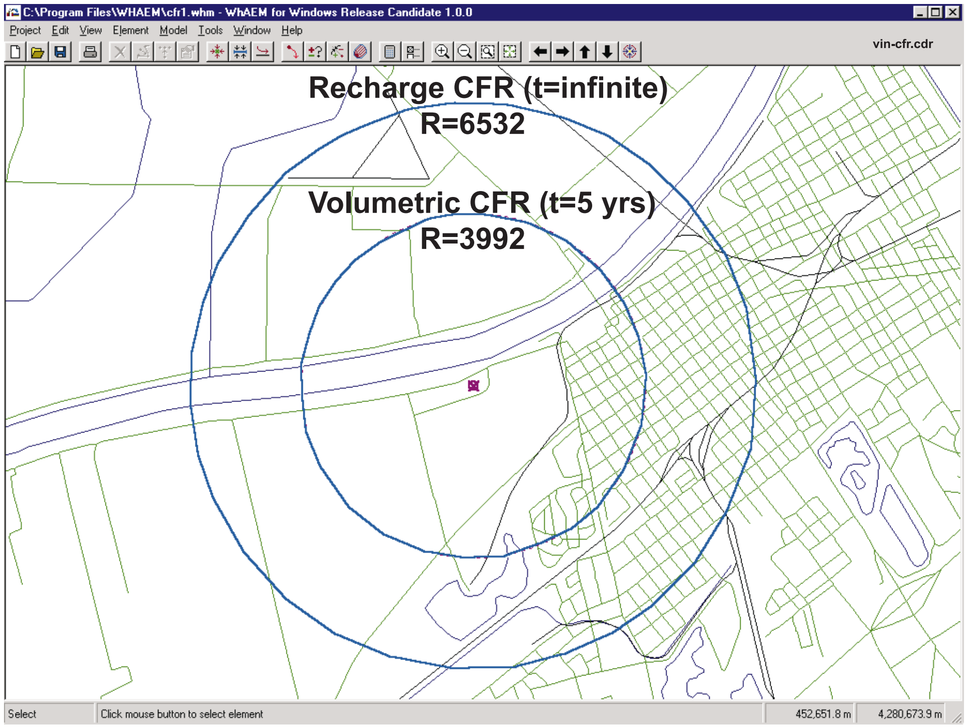


Figure 3.2: Calculated fixed radii for Vincennes wellfield based on recharge and volumetric methods.

handy, we suggest you use the Microsoft Windows calculator (Start > Programs > Accessories > Calculator). To draw the new radius on the screen, double click on the well, and edit the setback box and type in the new radius. After clicking **OK**, drop down the **View** menu and click on **Refresh**. You may have to zoom out to see the circle (setback zone). Draw the wellhead protection area (recall the exercise in previous chapter).

For the volumetric method, use equation 3.4, assume $Q = 370,000 ft^3/day$, aquifer saturated thickness $H = 67.5 ft$, the aquifer porosity is $n = 0.2$, and the pumping period is five years (1826.25 days). Draw the wellhead protection area.

Compare your results to Figure 3.2.

3.3 Well in Uniform Flow

Ambient flow, resulting from far field aquifer recharge due to precipitation and ground water exchanges with streams and lakes, may be approximated by a uniform flow field (straight streamlines) in the immediate vicinity of the well. The capture zone for the well in a uniform flow field will no longer be circular and centered about the well, but will be a somewhat elongated oval-shaped domain into the direction of uniform flow.

To determine this capture zone (e.g. by use of W*h*AEM) it is necessary to determine:

- direction of the ambient flow.
- the hydraulic gradient.
- the aquifer transmissivity.
- the pumping rate of the well.
- the desired maximum residence time.

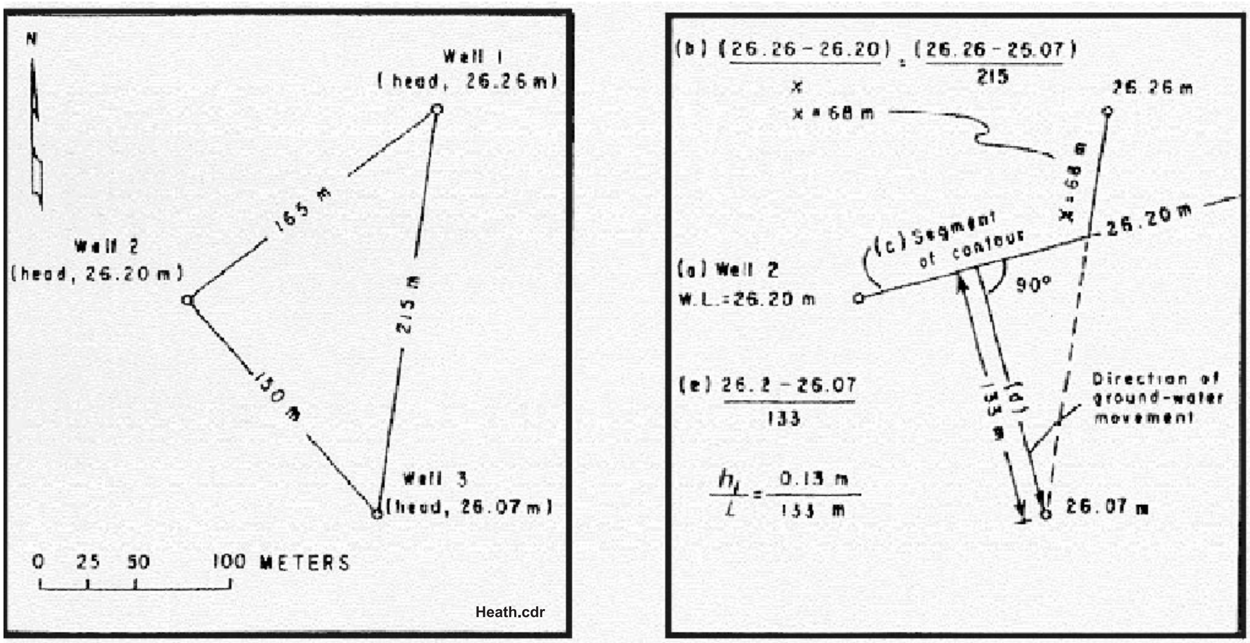


Figure 3.3: Procedure A for determination of an equipotential contour and direction of ground water flow in homogeneous,isotropic aquifer (after [Heath,1983]).

Given three water levels (average, static), it is possible to estimate the direction of the ambient flow and the hydraulic gradient [Heath,1983]:

1. Identify the well that has the intermediate water level.
2. Calculate the position between the well having the highest head and the well having the lowest head at which the head is the same as that in the intermediate well.
3. Draw a straight line between the intermediate well and the point identified in step 2. This line represents a segment of the water level contour along which the total head is the same as that in the intermediate well.
4. Draw a line perpendicular to the water level contour and through the well with the lowest (or highest) head. This indicates the direction of ground water movement in an isotropic aquifer.
5. Divide the difference between the head of the well and that of the contour by the distance between the well and the contour. This gives the hydraulic gradient.

The reader is referred to an on-line three-point gradient calculator at
http://www.epa.gov/athens/software/training/WebCourse/part-two/onsite/gradient3.htm.

A 3-point method based on the squared heads (water levels) has been shown to reduce bias in the estimate of the magnitude and direction of the uniform flow vector in heterogeneous unconfined aquifers, provided the monitoring wells have a significant separation distance, and that there are no sources and sinks in between [Cole, Silliman, 1996].

Be sure to do a search of the scientific literature (US Geological Survey, State Geological Survey) to find any studies of the regional aquifer system and the regional hydraulic gradient.

The aquifer transmissivity should be determined by a pumping test. This is an expensive procedure, and transmissivity is known to be scale dependent. Perhaps transmissivity measurements are available from locations not too far from the well.

The well in uniform flow solution is difficult to parameterize in practice. It is difficult to anticipate the average hydraulic gradient and direction of flow given limited synoptic observations of a transient phenomenon. It is difficult to separate out the local effects of the well, unless it is out of production for a period of time. For these reasons, caution is advised to the use of the well in uniform flow solution. The modeler is encouraged to respond to the uncertainty by generating a number of reasonable solutions, and encapsulating the union of solutions into a protective area. In other words, use the "wellhead area" drawing tool to draw an envelope around the set of capture zone realizations.

3.4 Exercise: Well in Uniform Flow, Vincennes, Indiana

Step 1 Determine the magnitude and direction of a uniform flow field near the Vincennes pumping center.

First we will give our project a new name. Open the base project — from the Menu, go to **Project** , and **Open Project** and select `vinbase`, then, from the Menu, **Project** , **Save as**, and enter `vinuni1`.

As a first estimate, we will attempt to characterize the uniform flow field by using the USGS topographic map and the USGS DLGV32 software and the Vincennes DRG. The "lakes and ponds" in this area are actually abandoned mines, and removed overburden gives a window into the elevation of the water table. We assume these mines act like large piezometers, and field observations confirm that their water levels do in fact respond to recharge events.

A note of caution is deserved regarding extracting water elevations from USGS topographic maps. These elevations reflect a snapshot in time (check the date of publication of the map), and may not reflect conditions related to your study. The Vincennes maps was photo-revised in 1989. The elevation values are accurate say plus or minus a foot. The spatial accuracy of the topographic lines are accurate say plus or minus 5 feet. These uncertainties are acceptable for this level of analysis.

Use the method of Heath and three points of known head: (1) Mirror Lake; (2) Otter Pond; and (3) the 400 foot topographic line crossing of the Wabash River.

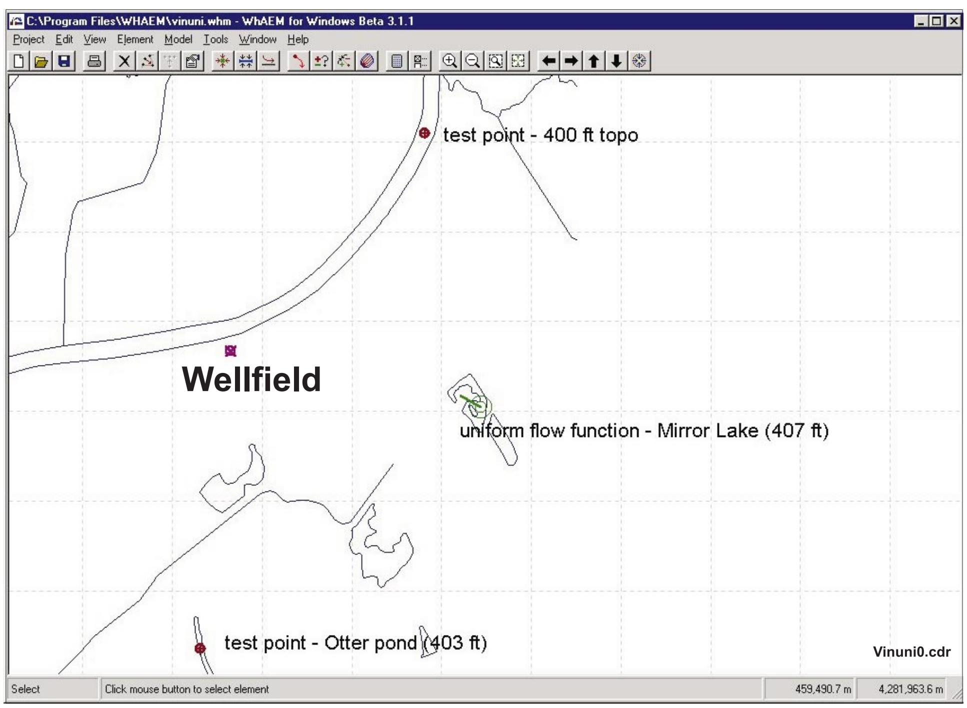


Figure 3.4: W*h*AEM view of test points used to calculate uniform flow vector.

Step 2 Use the uniform flow element in W*h*AEM to fit the estimated uniform flow.

Zoom to approximately the view shown in Figure 3.4, which includes Mirror Lake and Otter Pond. From the Menu, select **Element** , then **Uniform Flow**. Acknowledge the warning. Click the cursor over Mirror Lake. Enter in the elevation $407 feet$. Enter the gradient (for our case about 0.001). Enter the angle (for our case about 150 degrees).

Step 3 Enter the aquifer and contouring properties and test points.

From the Menu, select **Model** , and then select the **Aquifer** tab. Set the **base elevation** to $330ft$, the **thickness** to $100ft$, the **hydraulic conductivity** to $350ft/day$, and leave the **porosity** as 0.2. Figure 3.5.

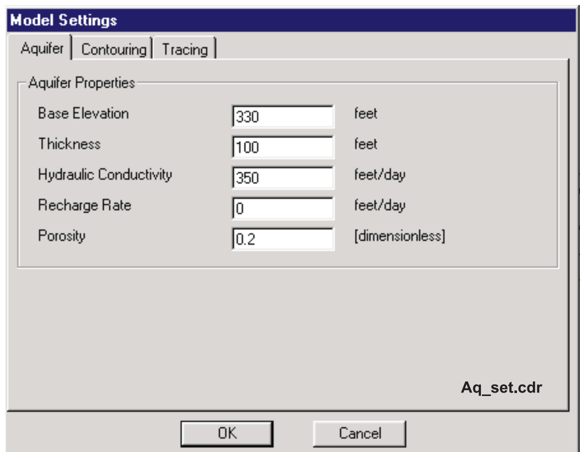


Figure 3.5: Aquifer settings dialog box.

Note: Do not specify a recharge rate when using uniform flow. Recharge effects are lumped into the far-field behavior of the function.

Click on **OK**.

Now set the **Contouring** properties. From the Menu, select **Model** , and then**Settings**, and click on the **Contouring** tab. Check the **Show Contours** box and select the radial button for **coarse** (resolution). Enter the **minimum contour** elevation of $390ft$, the **maximum elevation** of $430ft$, and a **contour interval** of $1ft$. Click on **OK**.

To test our conceptual solution, we may introduce so-called "test points" at locations of *known* head, e.g. Otter Pond ($403ft$ and utm 452325, 4277311) and the $400ft$ topographic intersection (utm 454815, 4283085) with the Wabash River, by selecting **Model** , then **Test points**, locate on the screen with a click of the left mouse button, and enter the elevations. The test points will store the difference between the model head and the observed head. The head differences at the test points are visually displayed with a scaled triangle, or can be queried by clicking on the test point (look at the status bar at the bottom of the screen when clicking a test point).

Step 4 Solve the model and plot the contour map.

From the menu select **Model** , then **Solve** (Alternatively, use the F9 mapped function key, or the smart icon Figure 3.7).

The hydraulic head contour map of this solution is shown in Figure 3.8.

Note: since our model heads will be close to the test point heads, the arrows designating the head difference will be too small to see. Just add or subtract about $5ft$ to a test point elevation and resolve the model. Now a triangle will show up. You may modify the test point appearance by selecting **Test Points** on the **View** menu.

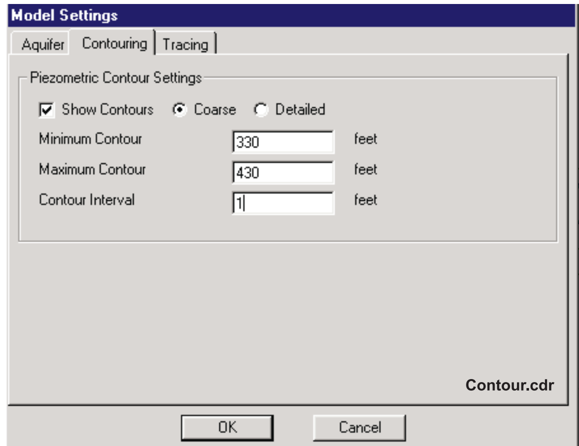


Figure 3.6: Contouring settings dialog box.

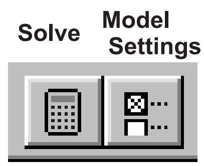


Figure 3.7: Solve icons.

Step 5 Enter the pumping rate and radius of the pumping center.

Locate the Vincennes pumping center (**Element** > **New** > **Well**). Enter in the well **pumping rate** of $370,000 ft^3/day$. Enter a **radius** of $4ft$. Figure 3.9.

Note: The large radius of $4feet$ is used because the pumping of several wells are concentrated in one fictitious well — the pumping center. Too small a radius would cause the aquifer to dry up near the well and cause trouble when tracing particles.

Enter **OK**.

Step 6 Plot a capture zone based on 5 years of residence time.

Double click on the well, and check the box **Trace Pathlines Emanating from Well**, and set the **Number of pathlines** to 20. Click on **OK**. Go back into the **Model** , **Settings**, and select the **Tracing** tab. Check the box **Compute particle paths**. Accept the default **Step size**, and notice the **Maximum travel time** of 1826.25 days (5 years). In the Contouring tab, click off the show contours box. Click **OK** and click the calculator button on the tool bar (re-solve). You can add the tic marks by going to **View** , and select **Pathlines**, then **Show Time Tics**, and check **Every 1 years**. Draw the wellhead protection area around the trace lines. The graphics should look similar to Figure 3.10. You are encouraged to try a number of equally valid uniform flow field solutions, and vary the Model setting parameters to get insight into the sensitivity of the solution to the parameterization.

The solution is becoming more realistic. However, we still do not account for the presence of the Wabash River and other hydrological features in the area! We shall do that in the next chapter.

Step 7 Compare solutions.

It is interesting to do a verification of the well in uniform flow solution in comparison to the CFR volumetric. Click

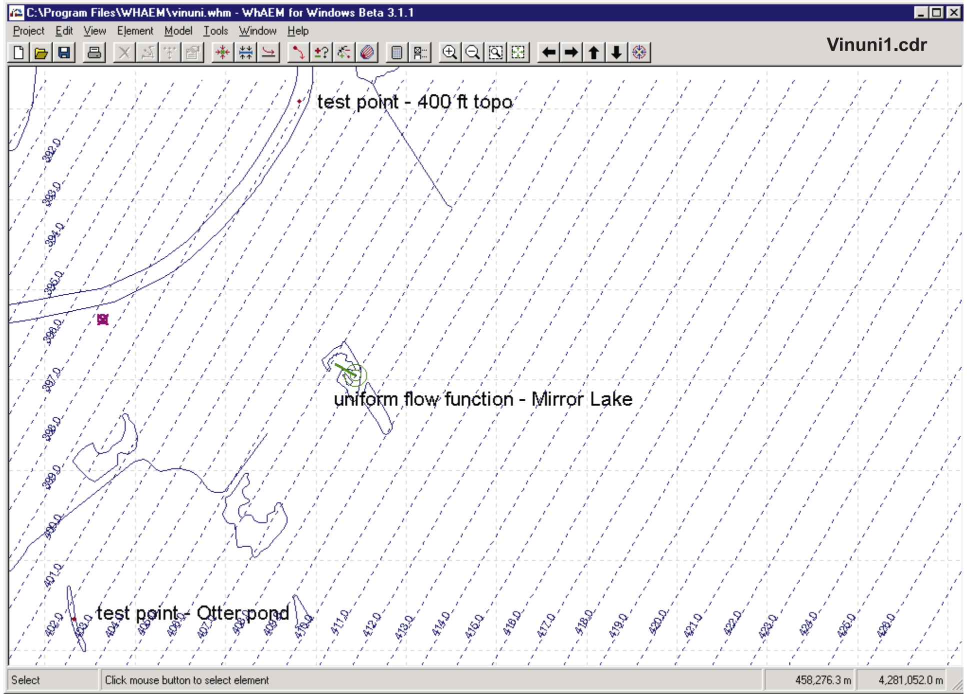


Figure 3.8: Hydraulic head contours of uniform flow field with test points.

on the well, enter the 5 year CFR volumetric previously calculated (R=3992 ft). Change the uniform flow gradient to a very small number, say 0.00001, and plot the 5 yr capture zone. Notice that the capture zones become essentially equivalent. Figure 3.11.

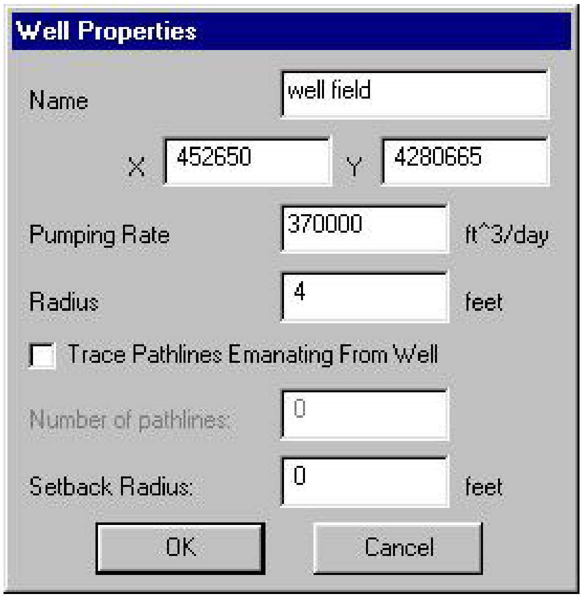


Figure 3.9: Well dialog box.

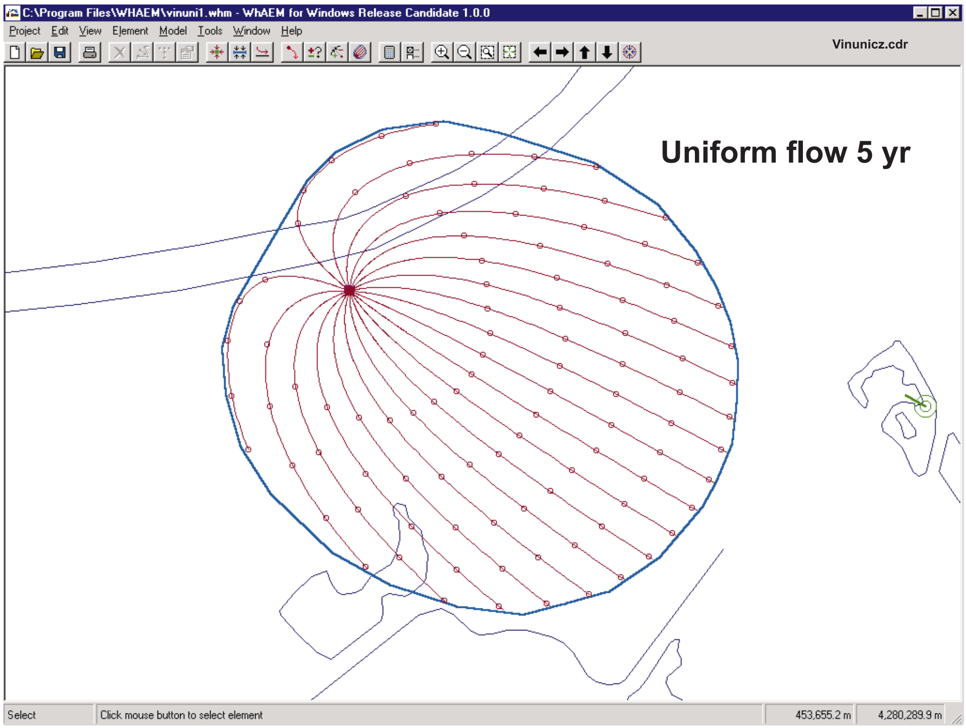


Figure 3.10: Capture zone based on 5 years residence time in uniform flow field.

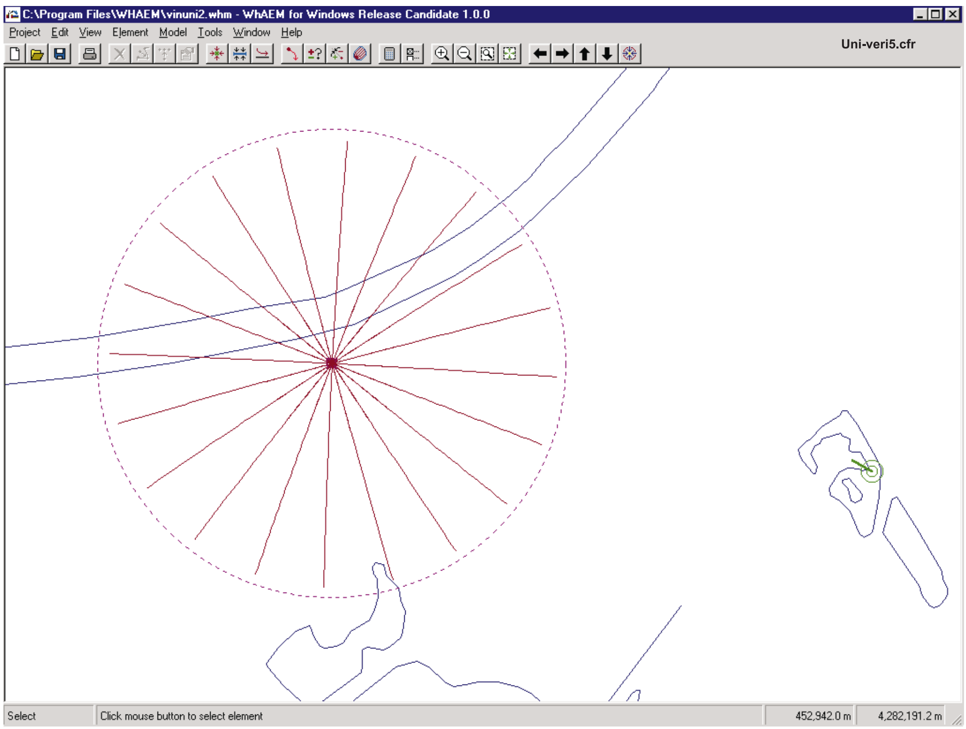


Figure 3.11: Capture zone based on 5 years residence time based on CFR volumetric and tracelines for well in uniform flow field (zero gradient).

Chapter 4

PROTECTION ZONES III — FLOW BOUNDARIES CRITERIA

In the previous analyses we have ignored the presence of hydrological boundaries. Instead, we lumped their effects near the well into a uniform flow field. In this chapter we will include the most important hydrological boundaries and aquifer recharge explicitly. To do so we will use the full power of W*h*AEM . We will progressively refine the complexity of our hydrogeological conceptual model using the Vincennes example. But before doing so we will explain briefly how W*h*AEM works.

4.1 Introduction to the Analytic Element Method

W*h*AEM uses the analytical element method to solve ground-water flow subject to hydrological boundary conditions. Analytic elements are mathematical functions that represent hydrogeologic features in a ground-water flow model. For instance, a meandering creek or river may be represented by a string of straight line elements, which approximates the geometry of the stream. In W*h*AEM , each of these line elements is associated with a "line-sink function", which represents mathematically the ground-water inflow, or outflow, into the stream section. The sink density of the line-sink equals the ground-water inflow into the stream section. Each stream section is likely to have a different ground-water inflow rate and thus a different sink density. These sink densities are not known in advance. What is considered known are the heads underneath the stream sections. For instance, in W*h*AEM it is assumed that the head underneath the center of each line-sink is equal to the average water level in the stream section it represents. W*h*AEM has as many known heads at line-sink centers as it has unknown sink densities for the line-sinks. The unknown sink densities can then be calculated by solving a system of (linear) algebraic equations, see [Strack,1995] and [Haitjema,1995].

Other examples of analytic elements are wells (point sinks in two-dimensions), line doublets or "double layers" to represent no-flow boundaries in W*h*AEM , and a sink disc to model areal recharge due to precipitation (using a negative sink density to create infiltration). Once all sink densities and doublet densities are calculated — the solution procedure in W*h*AEM — the head and average ground-water flow rate can be calculated at any point by adding the influence of all the line-sinks, point-sinks, line doublets, and the sink disc. This is the principle of superposition.

Note: the ground-water velocity is calculated by adding "derivative functions" for the analytic elements, which have been obtained analytically and are programmed into W*h*AEM . For details on the mathematical functions and on the mathematical procedures to enable the superposition of solutions of both confined and unconfined flow, the reader is referred to [Strack,1989] and [Haitjema,1995].

Analytic elements are defined in W*h*AEM by clicking the **Element** menu, and selecting **New**.

4.1.1 Line-sinks

Line-sinks are used to represent streams (creeks, ditches, and rivers) and lake boundaries. A line-sink in W*h*AEM has a constant sink density (constant groundwater extraction rate along the line element). The sink density or "strength" of a line-sink that represents a stream section or a section of a lake boundary is in general not known. In W*h*AEM this is handled by specifying a piezometric head at the center of the line-sink, which is selected equal to the average water level in the stream section or lake that is represented by the line-sink. For every unknown line-sink strength there exists one known head. This leads to a system of equations that is solved for the unknown strength parameters of the line-sinks. Every change in data in the W*h*AEM model, therefore, requires a new solution procedure to recalculate the strength parameters. The line-sink strengths represent the ground-water extraction rates of the line-sinks, in volume per time per unit length of the line-sink (stream or lake boundary).

The use of line-sinks along lake boundaries implies that in W*h*AEM a lake receives or loses ground water along its boundary only. This appears to be a good approximation of reality when the size of the lake is large compared to the saturated thickness of the aquifer. For streams that have a width that is large compared to the aquifer thickness, the realism of the line-sink representation may be improved by positioning line-sinks along both sides of the river.

The number of line-sinks required to represent a stream depends on two factors: (1) the need to follow detailed stream geometry, and (2) the need to allow for variations in the ground-water discharge or recharge along the stream or lake boundary. Representing stream geometry is more important in the near field (immediate area of interest) than in the far field. Similarly, the need to use many small line-sinks to follow discharge or recharge variations along the stream is most pressing in the near field, particularly near a high capacity well which may draw water from the stream. Consequently, surface water features in the area of interest (near field) should be represented with more and smaller line-sinks than surface waters in the far field, remote from the area of interest.

Line-sinks are defined in W*h*AEM by selecting the **Element** menu, and selecting **New** and then **Line-sinks**.

4.2 Exercise: Vincennes and Line-sinks

Step 1 Annotate the basemap with elevations.

It is useful to annotate your basemap with estimated surface water elevations at those streams that you intend to include in the model (represent by line-sinks).

Open the database file `vinbase.whm`. Save this as the new database `hydro1`. Minimize the W*h*AEM window. Open the USGS 7.5 minute topographic map for Vincennes with the dlgv32 program. Find the location where the $400ft$ topographic contour crosses the Wabash River north of the city. Note below the UTM location of the $400ft$ contour:

$$utm - x(easting) = \underline{\hspace{4cm}} \tag{4.1}$$

$$utm - y(northing) = \underline{\hspace{4cm}} \tag{4.2}$$

Now close out dlgv32, and restore the W*h*AEM window. **Zoom In** to the location of the $400ft$ contour. From the Menu, select **Edit**, and then **Add text**, move the text cursor to the proper location (using feedback on the UTM location of the cursor from the bottom status line) on the stream and click the left mouse button. Type the contour elevation 400 feet in the dialog box, check the **Hydrography Label** option, and click **OK**. The label appears in the map and the text cursor reappears. You would need to repeat this procedure to add all the rest of the hydrography elevations, i.e. elevations where topography contour lines cross the surface water features. To end entering hydrography (text) labels click the right mouse button. It is often sufficient to add hydrography labels near the map boundaries and near confluences of streams. When creating line-sink strings you will only be prompted for a head at the start of the string and at the end of the string. The program will interpolate between these heads.

We have created a text file for you with elevations so you can complete your basemap. The label file must be an ASCII text file (`filename.TX`) in which each line has the following format:

$$utm - x \qquad utm - y \qquad h \qquad label \tag{4.3}$$

where x and y are the (basemap) coordinates of the lower left corner of the text, where $h = 1$ for hydrography labels (water levels in surface waters) and $h = 0$ for any other text label. The label is the water level or text to be printed on the map. The text labels will be added to the current project database file. To import the file containing text labels select the **Tools** menu, then **Import**, and then **Text Label File**. Select the file `Hydro Example.tx`. In order to view the hydrography labels on the basemap, you may need to toggle them on (**View** > **hydrography labels**). This is also a good time to import the hydrography from the Frichton quad to the east. You will need to use the map browser to import the BBMs (vi1*07.bbm), as described in the Exercise: Vincennes, Indiana of Chapter 2. Add the basemaps to the layout (go to **Project** , **Basemap Settings**, and **Add BBMs**).

Step 2 Represent the Wabash River with a string of Line-sinks.

At this point, it is recommended that you set your window to frame the region including the 395 foot elevation and 400 foot elevation of the Wabash River. Then, from the menu select **Element** , and then **New**, and then **Linesink**, or alternatively, click on the Line-sink smart icon Figure 4.1. You will be prompted for the name of the line-sink string

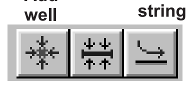


Figure 4.1: Elements smart icons.

about to be entered. Let's start with Wabash River, hence type `Wabash`. Next fill in the **Starting Head**. This is the water level in the stream at the start of the line-sink string you intend to create. In our case, start at the big meander of the Wabash River west-south-west of Vincennes where the elevation contour crossing the river is 395 feet according to our hydrography labels. Type 395 in the box and click **OK**. Move the cursor to the point on the stream where the 395 topo line crosses the Wabash River, east bank. Click the left mouse button to enter the first vertex. Move the cursor following the river bank upstream to the north (a rubber band shows the line-sink location) and click the left mouse button again, setting the next vertex. Continue this process until you want to end the string. Roughly follow the river with line-sinks about the length of the grid cells, if you have them turned on. Only near the well-field you should use shorter line-sinks and portion them along the east bank of the river — the south side of the river closest to the well field here. We suggest ending the string with a left click where the $400ft$ topo line crosses the Wabash River. And then cClick the right mouse button. The dialog box reappears and now type the **End Head**, which is $400ft$. Click **OK** to complete the definition of this line-sink string.

That completes your first line-sink string. At the center of each line-sink in the string a head will be specified by W*h*AEM based on a linear interpolation of the starting head and ending head along the line-sink string.

We recommend you represent the other side of the Wabash River with a string of line-sinks, particularly near the wellfield. Estimate a starting head and position of 397.5 feet, and continue to the 400 feet.

Step 3 Surround the wellfield with hydrologic (line-sink) boundaries and solve.

You should attempt to locate head specified boundaries (line-sinks) in all directions projected out from the well-field, putting more detail (i.e. using more line-sinks) in the near field and less detail in the far field. In our steady state model, we will include the perennial streams, or streams that are flowing all year round. In the Vincennes wellfield area, those include City Ditch, Mantle Ditch, Kelso Creek, Ditch 2, Ditch 3, and the Wabash River, of course [Shedlock, 1980]. Perennial streams show up as solid blue lines in USGS topographic maps, and dashed if ephemeral.

Create line-sinks representation of the perennial streams. Add the Vincennes well-field with the same properties as before. Your model should look something like Figure 4.2.

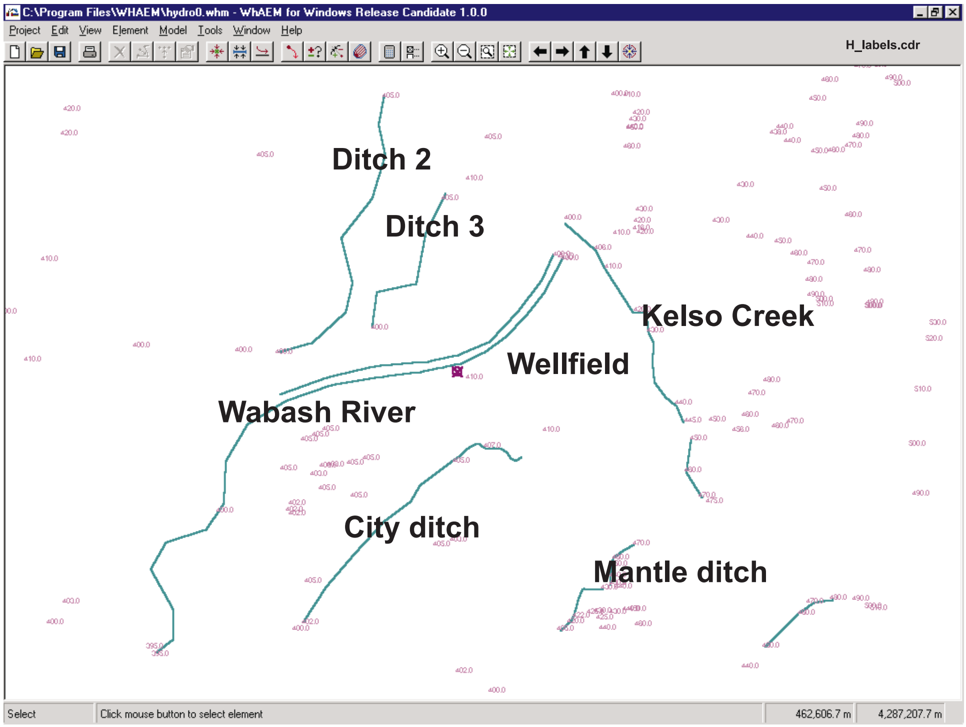


Figure 4.2: Hydrography labels and line-sinks representing the Wabash River between elevations $395ft$ and $400ft$ and perennial streams and ditches.

Try to use short length line-sinks in the near field and longer length line-sinks in the far field. Try to keep the total amount of line-sinks below 200 for efficient model operation. You can check this by clicking **Model** and **Model size**.

You may change the location or properties of wells and line-sinks as follows. Click on the well or a line-sink vertex in the string you want to edit. The well or line-sink string will become highlighted (red). Click on the **Edit** menu and select **Properties, Move, Delete**, or **Refine**. For line-sinks you will be asked whether you want to delete only the selected vertex or the entire string. When selecting **Refine**, a vertex is added midway in the line-sink on either side of the vertex that was selected (highlighted in red).

Let's refine the line-sink distribution of the Wabash River near the the wellfield. This is the area of induced recharge from the river to the well, and the solution will be improved with refinement. Click on a vertex of the line-sink string. Next click on *Refine* on the **Edit** menu. You may also click on the refine icon (the third to the right of the printer icon). Acknowledge the warning. Notice the two added vertices (dots) on either side of the vertex you clicked on. Repeat this for one or two other vertices of the Wabash River line-sink string near the well.

From the Menu, select **Model** , and reset your **Settings**, including **Aquifer** and **Contouring** parameters as shown in Figure 4.3. Let's add areal recharge of 12.1 inches per year (0.00276 ft/day).

Step 4 Solve and plot the 5 year capture zone for the well field.

In **Model** , **Settings**, select the **Tracing** tab and check the **Compute Particle Paths**. Double click on the well

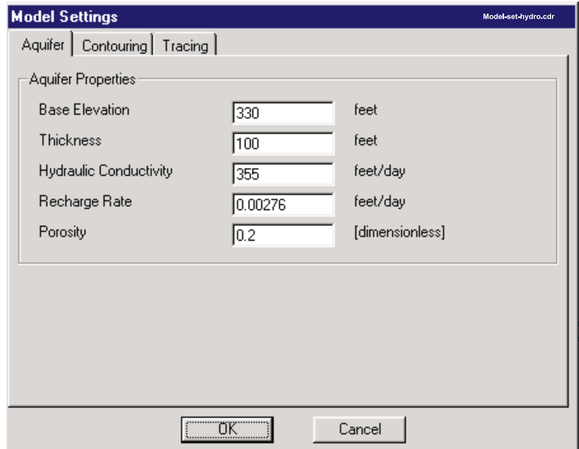


Figure 4.3: Model settings, including areal recharge.

and check the box **Trace Pathlines Emanating From Well**. Select **Number of Pathlines** 20. Click **OK** and then **Solve**. Draw the wellhead protection area. Figure 4.4.

Note: if no pathlines appear, ensure they are turned on under the **View** menu and that your aquifer parameters are correct; if heads are drawn down to the aquifer bottom no pathlines will appear!

Step 6 Check the solution for integrity.

Select **View Results Table** from the **Model** menu, click on **View** and on **Linesinks**. You are looking at the vertices of the line-sink strings. Look further to the right in the table to ensure that the "Specified Head" and "Modeled Head" for all line-sinks are nearly the same (less than one percent error). This ensures a solution that meets the boundary conditions, at least at the line-sink centers. Again, further to the right in the table are the "Strength" and the "Sink Densities" for each line-sink (in ft^2/day).

The "Sink Density" is the ground-water inflow rate into the stream. The "DP Strength" (Dipole Strength) is the sink density times the length of the line-sink (in ft^3/day) and accumulated along the line-sink string. The "DP Strength", therefore, is the total amount of water extracted by the line-sink string in one day up to the line-sink in question. It is valuable to compare the "DP Stength" to a base flow separation at a USGS gaging station, in order to test the reasonableness of the model water balance (which is insured in the analytic element method) in comparison to the field.

It is useful to compare the model predicted heads to observations of heads at monitoring wells. Fortunately, the USGS has reported a series of measured water levels in the Vincennes area for the period January 23-25, 1978 [Shedlock, 1980]. These water levels have been stored in a Test Point file. To import this file, select **Tools** and then **Import** the file `vin-mw.tp`. The view will show the test point locations as triangles, with the size and direction related to the difference between model head and observed head. Figure 4.5. Click on the triangle to report the error on the bottom status bar. Notice we have some large errors of the order of 16 feet in the model to the south. These will be discussed in the next section.

Calculated heads are expected to differ from observed heads for many reasons, most importantly because the model aquifer is merely an abstraction of the real aquifer system. A good model will show test point triangles that point both up and down, whereby the differences in head are not too large. A good model will also show a rather random distribution of up and down arrows, instead of having all up arrows clustered in one area and all down arrows in another.

In an ideal homogeneous single aquifer some general rules apply for heads that are too high or too low. Heads that are consistently too low close to the well field suggest too low a transmissivity in the model. Heads that are consistently too high in areas of ground water mounding may also indicate too low a model transmissivity or too high an areal

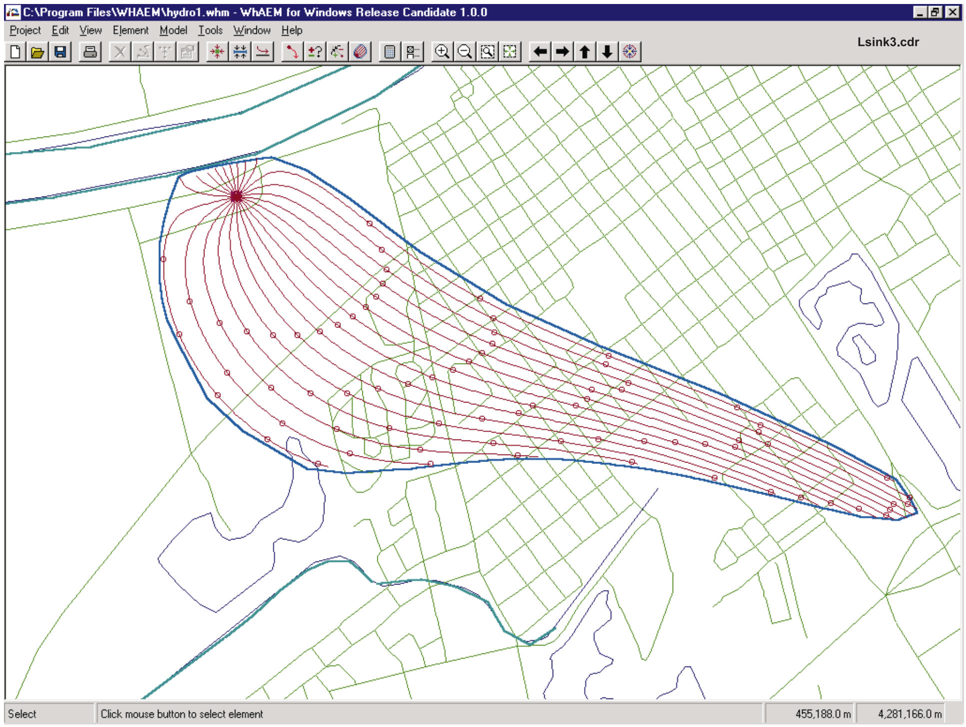


Figure 4.4: 5 year capture zones including the influence of hydrologic boundaries.

recharge rate (or both). When the actual aquifer is significantly stratified or, in fact, consists of several vertically stacked interconnected aquifers, discrepancies between observed and calculated heads may also be explained based on the relative depth of the piezometers (wells) in the field. In most cases, shallow piezometers in a stratified aquifer tend to show higher heads than predicted in a homogeneous aquifer, while deep piezometers tend to show lower heads. Only close to discharge areas, such as streams or lakes, may this trend be reversed.

Heads that are too high or too low may also be the result of improper representation of surface waters. For instance, the headwaters of a creek may artificially raise the ground water table in W*h*AEM by infiltrating large amounts of water (which these headwaters don't have to give). Such stream sections should not be represented by line-sinks in W*h*AEM .

4.3 Geologic Contacts and No-Flow Elements

The geology of the Vincennes study area deserves a closer look at this point as we refine the conceptual model. The area is underlain by unconsolidated sediments shown in Figure 4.6. The sediments were deposited by glacial processes in the Wabash River valley during the Pleistocene Epoch and were reworked by wind and water. The outwash pinches out a the margins or the river valley and generally rests directly on the underlying bedrock, as shown in Figure 4.7. A couple of rock "islands" outcrop just south of the wellfield.

Ideally, we should represent the high permeable rock and till explicitly in our model. W*h*AEM2000, however, currently lacks the facility to include zones of differing (zoned) permeability. In W*h*AEM open strings of line doublets are used to create no-flow boundaries, which may be positioned along the boundary of the outwash or channel deposits to approximate the effect of an absolute reduction in permeability. These no-flow boundaries should be extended into the far field to ensure their complete effect in the near field.

Note: In more sophisticated analytic element models, such as GFLOW (Henk Haitjema, Indiana University), SLAEM (Otto Strack, University of Minnesota), TWODAN (Charlie Fitts, University of Southern Maine), SPLIT (Igor Jankovic, SUNY Buffalo),

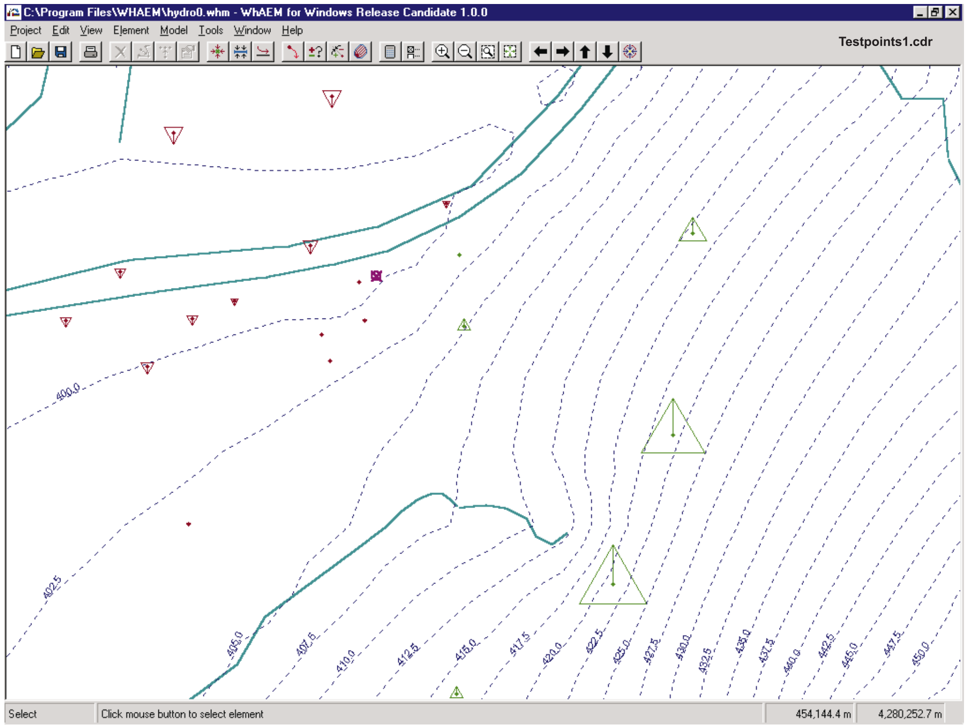


Figure 4.5: Model head contours compared to field observations at monitoring wells.

such zones are defined by polygons of line doublets which delimit zones of differing permeability or saturated aquifer thickness.

W*h*AEM conceptual models with and without these no-flow boundaries may be seen as bounding cases of the real situation, at least for the property of heterogeneous hydraulic conductivity distributions. If these two extreme models do not significantly affect the time of travel capture zones, no further (more sophisticated) modeling seems necessary. On the other hand, if the two extreme models lead to drastically different time of travel capture zones a more sophisticated model than W*h*AEM is needed to more realistically include the hydraulic conductivity variations.

4.4 Exercise: Vincennes and line-doublets (no flow boundaries)

Step 1 Import the hypsography (topographic elevations) BBMs into the basemap.

First, save this project as `noflow1`. Add the BBM files *vihpf06, vihpf07* to the base map. The files are stored in the default directory. We will infer the rock outcrops from the sharp topographic changes to the east of the city of Vincennes, and to the south of the wellfield.

Step 2 Create the no-flow boundary at the topographic contact between outwash and rock.

From the menu, select **Element** , **New**, and **No-Flow**. Name the feature "Outcrop" and click **OK**. Use the mouse create vertices along the boundary (left click) and end (right click). Do the same for the island outcrops south of the wellfield. See Figure 4.8.

We suggest removing the line-sinks that intersect or are to the east of the no-flow elements (click on string, then press delete key). You should avoid crossing line-sink elements and no-flow elements to avoid numerical difficulties. The link-sink elements to the east of the no-flow elements are now hydrologically separated from the wellfield and are irrelevant to the local capture zone solution.

Step 3 Solve and check the calibration.

Step 4 Plot the 5 year capture zone.

Double click on the wellfield, and release around 20 pathlines. Check the **Model Settings**, and **Solve**. In **View** set the **Pathlines** to **Show time tics** to **every 1 year**. Draw the wellhead protection area.

4.4.1 Discussion

Apparently, the presence of a no-flow boundary has a significant effect on the flow patterns in the outwash, particularly on the capture zone for our well field (compare Figure 4.4 and Figure 4.10). If some water enters the outwash from the till and rock formations to the east, the capture zone will tend to extend further to the east than for the case the rock and till are considered impermeable. It is possible to redo the analysis with a more sophisticated model, which includes the rock and till region explicitly. However, such a modeling effort is costly, as much more data in a much larger region must be collected.

In the face of uncertainty, it is prudent to present more than one piezometric contour map and more than one time of travel capture zone. The impact of the most sensitive parameters on the capture zone should be illustrated by presenting the different capture zones and clearly explaining the different parameter choices that lead to them. It is much more convincing to show that, for instance, a fifty foot per day difference in hydraulic conductivity does not noticeably change the capture zone than argue at length why the particular value chosen for the model is the right one. You may annotate the graphics (piezometric contour maps or capture zones) directly on the screen by use of the **Add Text** option on the **Edit** menu. The maps may be printed using the Printer setup and **Print** options on the **Project** menu. You may also export the graphics in DXF format or export the piezometric contour and path line data in SURFER format for further post processing. DXF maps can then be converted to binary base map format using the **Tools** and **Convert** sequence.

Haitjema and Kelson investigated the influence of further complexity on the capture zones for Vincennes [Haitjema,1995]. They used the analytic element code GFLOW [Haitjema,1995] to include the influence of the low hydraulic conductivity of the rock outcrops. They used the finite difference code MODFLOW [McDonald and Harbaugh, 1988] to represent localized three-dimensional flow, anisotropy, and resistance between the river and the aquifer. In carrying out this modeling, progressively more complex conceptual models were tested. It appeared that three-dimensional effects did not impact the capture zones, but different values for the resistance of the Wabash River bottom did. The reader is directed to Chapter 6.1 in [Haitjema, 1995] for a full discussion.

How do you know if resistance in important in your field study? You have resistance if there is a significant difference between water levels in the stream and heads below the stream.

W*h*AEM does not currently support bottom resistance on line-sinks to model the resistance to flow into or out of a stream. In practice, this resistance is difficult to parameterize because it is not practical to measure it directly in the field. In full-feature models, such as MODFLOW, resistance on rivers is often used during hypothesis testing, which yields solutions with varying degrees of water pumped from the stream. The capture zone presented in Figure 3.10 may be seen as the extreme for infinite resistance (no water drawn from Wabash River), while W*h*AEM offers the other extreme in Figure 4.4 and Figure 4.10 (no resistance to flow from Wabash River into the aquifer). To get an impression of the effect on the capture zone in either Figure 4.4 or 4.10, you may delete some line-sinks along the Wabash River immediately opposite the well. This will eliminate or drastically reduce the flow from the river to the well, and enlarge the capture zone upgradient from the well. Future versions of W*h*AEM are planned to include resistance line-sinks.

You may use the results of Figure 4.4, Figure 4.10, and Figure 3.10, or with some capture zones from runs with parts of Wabash River removed, to construct a protective envelope of capture zones as the wellhead protection area.

More sophisticated models (including resistance line-sinks) may lead to smaller capture zones and wellhead protection areas (see Figure 4.11), which has been produced with GFLOW [Haitjema, 1995]. In Figure 4.11, "composite capture zones" are depicted, based on the bounding capture zones of reasonable solutions. The final capture zones were produced in GFLOW using only 2D flow, but including resistance to flow from or into Wabash River.

Other professional analytic element modeling packages include WINFLOW (http://www.groundwatermodels.com/), TWODAN (http://www.fittsgeosolutions.com/), and SLAEM (http://strackconsulting.com/home/). The reader is encouraged to follow developments of ArcFlow which is based on the solution engine SPLIT by Igor Jankovic, State University of New York-Buffalo, and the ARCVIEW interface by the Minnesota Department of Health [Blum, 2000].

We have not introduced the concept of anisotropy in the hydraulic conductivity distribution, that is having different values depending on the direction of measurement. Anisotropy is known to influence the capture zone [Cole, Silliman, 1997]. There is the temptation to represent a highly fractured rock aquifer as an equivalent porous medium with anisotropic hydraulic conductivity, at least at the regional scale; this should be done with caution in fractured carbonate rock aquifers, [Kraemer, 1990],[Podgorney, Ritzi, 1997]. W*h*AEM2000 should not be used in aquifers with a highly anisotropic hydraulic conductivity distribution.

We have not introduced the concept of dispersion to this point. The capture zones presented in this document represent average water residence times in the subsurface. These residence times more closely represent the breakthrough time of the mean concentration of a conservative tracer at the well. If you wanted to represent the first arrival of the tracer in your delineations, and thus capture the initial breakthrough of a potential contaminant, you would need to incorporate macroscale dispersion. Characterizing dispersion in capture zone models is still a topic of research [Maas, 1999]. In practice, incorporation of a margin of safety may be prudent when presenting residence time capture zones.

4.5 Conclusion

W*h*AEM2000 is a computer tool to support step-wise and progressive modeling and delineation of source water areas for pumping wells. Our case study moved from arbitrary fixed radius, to calculated fixed radius, to well in uniform flow, to modeling with hydrologic boundary conditions only, to modeling with hydrologic and geologic boundary conditions. Each solution was conceptually more sophisticated, and we assume that the corresponding capture zones were progressively more realistic. The emphasis of the W*h*AEM project on "ease-of-use" and computational efficiency does not release you, the modeler, from responsibilities in justifying the conceptual models, and defending the reasonableness of the solutions. We emphasized uncertainties in conceptualization of boundary conditions in our case study, but uncertainties in parameterizations are also important. W*h*AEM2000 is public domain and no cost software, and while it is intended to capture the basics of ground water modeling in support of State efforts in source water assessments and wellhead protection, it is also intended to stimulate innovation in software design and modeling practice in the private sector.

One more time, "Keep your *ground water* models as simple as possible, but not simpler." Good modeling!

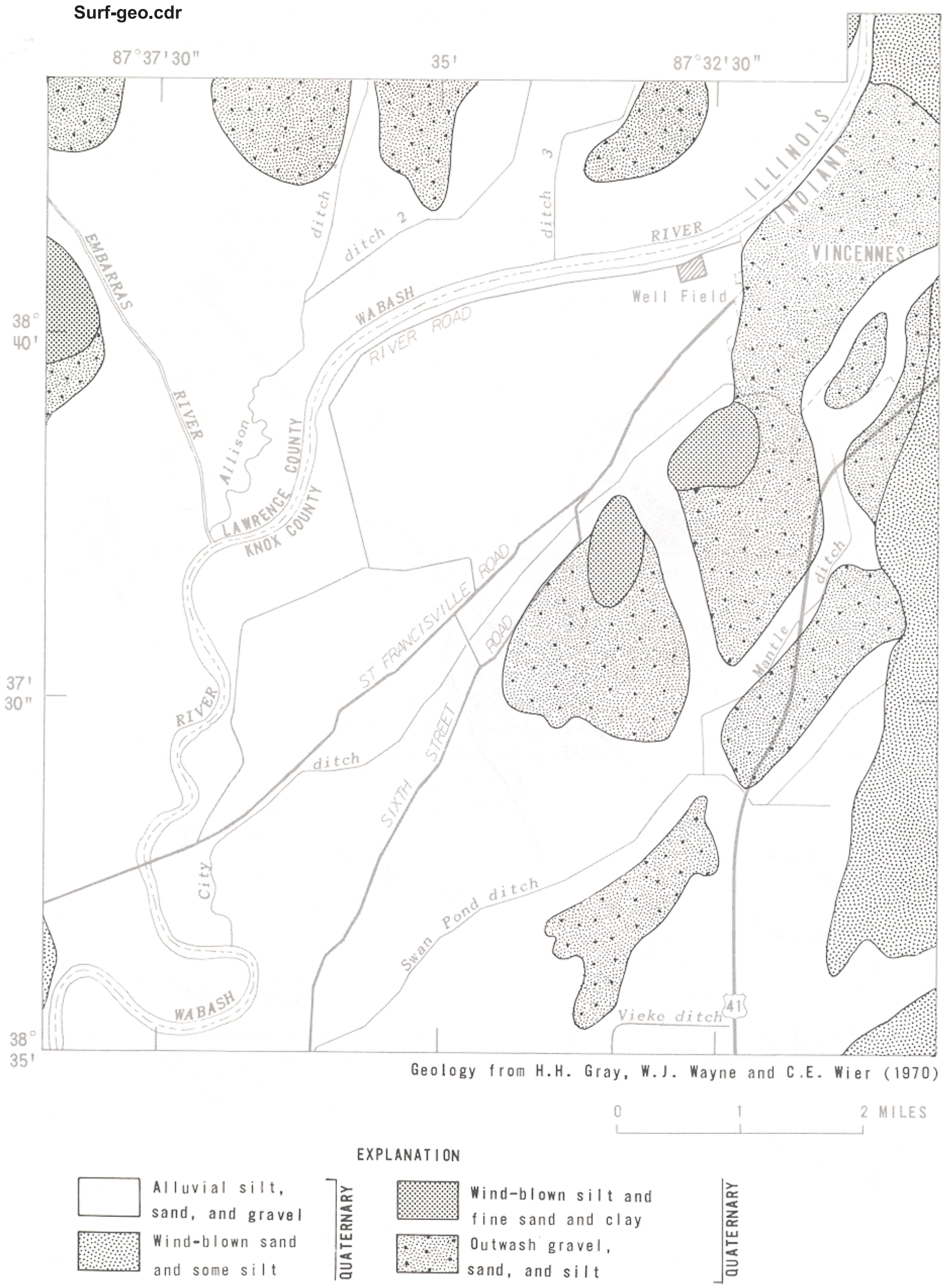


Figure 4.6: Surficial geology near Vincennes, Indiana. [Shedlock,1980]

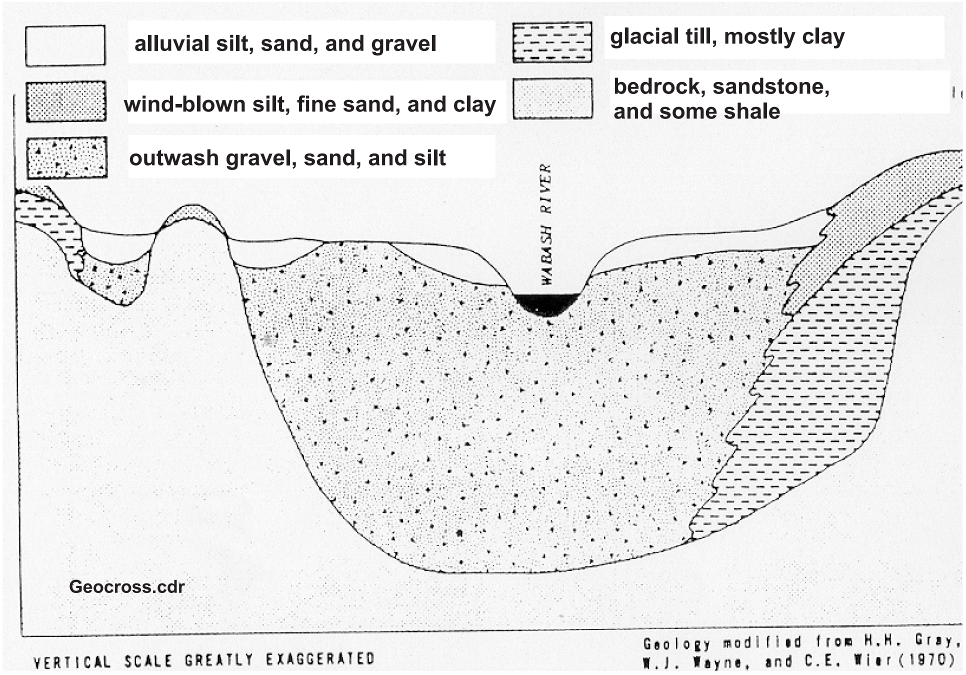


Figure 4.7: Generalized geologic cross section of the Wabash River Valley near Vincennes, Indiana [Shedlock,1980]

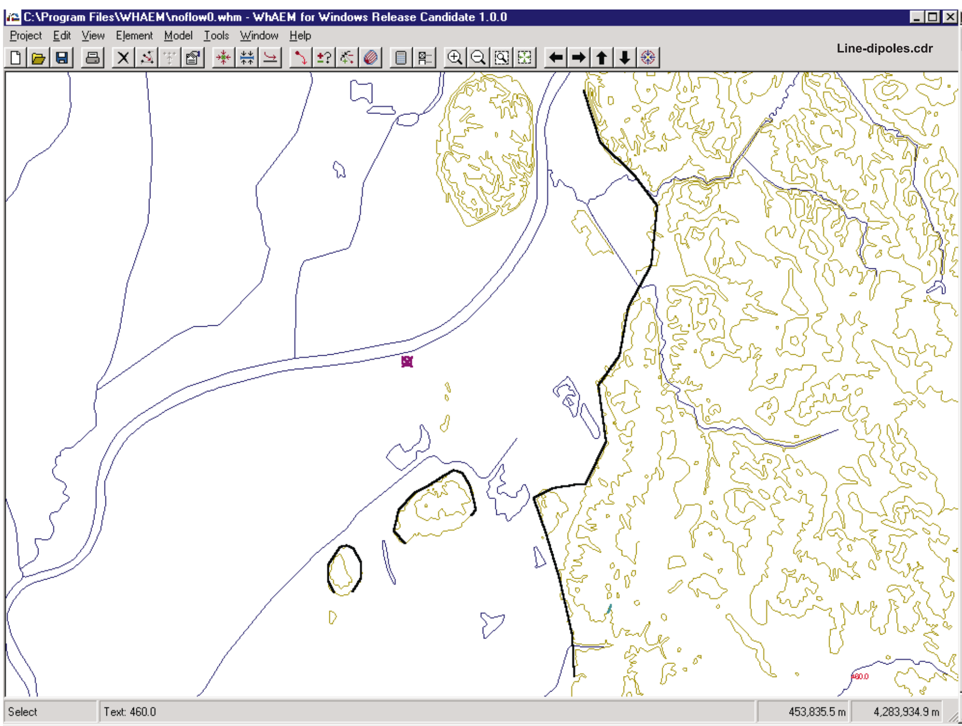


Figure 4.8: Superposition of no-flow elements along the geologic contact inferred from the topographic contours.

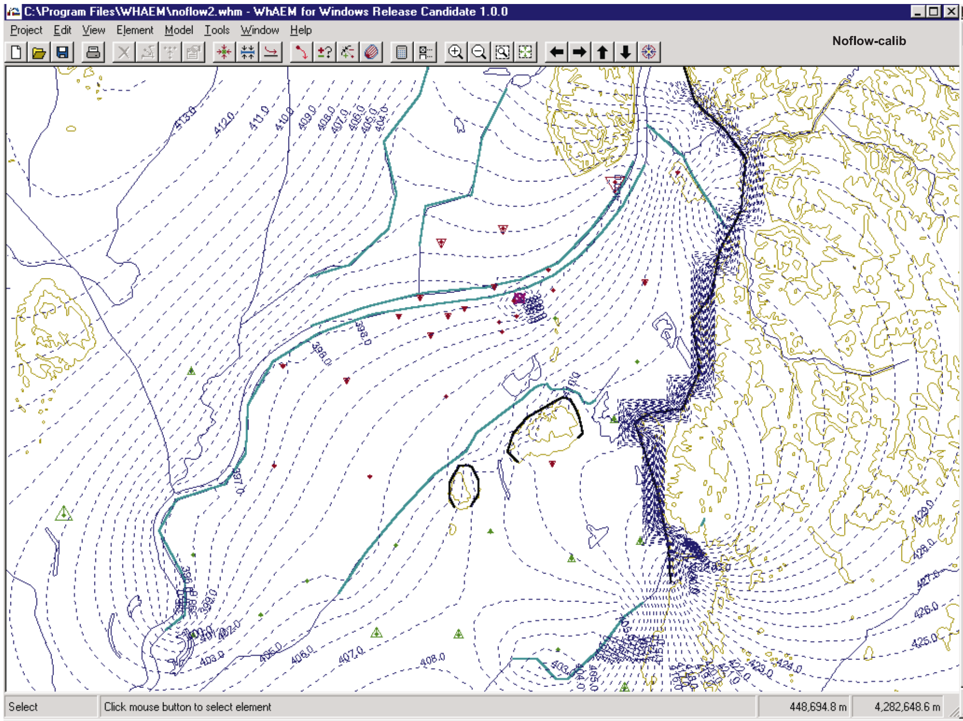


Figure 4.9: Hydraulic head contours and test points, including the no-flow elements.

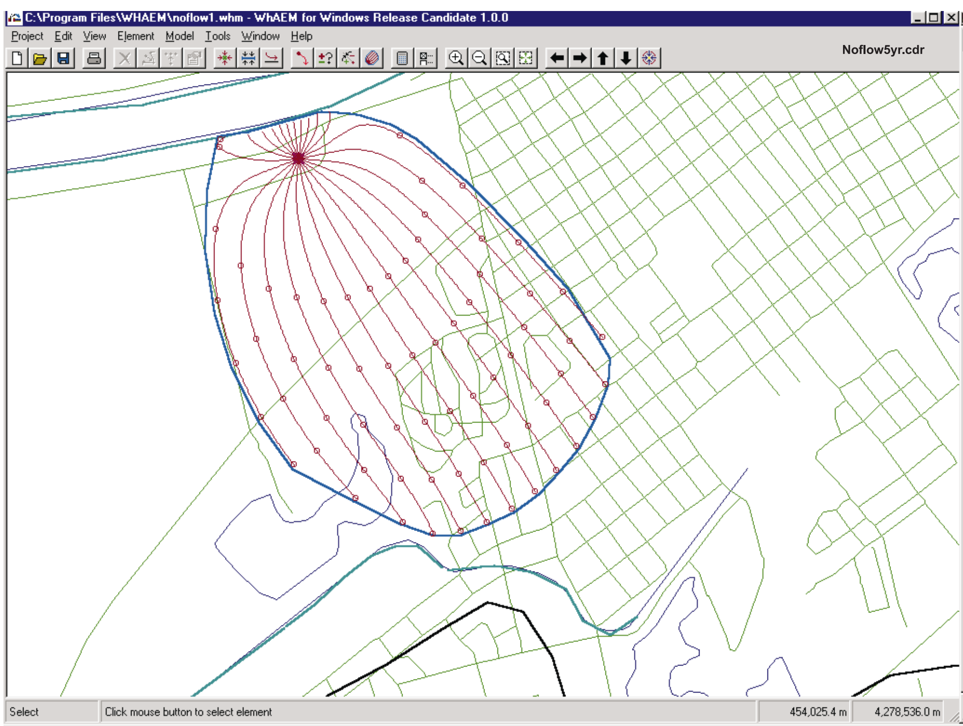


Figure 4.10: 5 year capture zone solution including the influence of hydrologic and no-flow boundaries.

Figure 4.11: Composite time of travel capture zones with 2-,5-, and 10-year isochrones for the Vincennes well field using the full-feature analytic element model GFLOW (after [Haitjema,1995]).

Appendix A

Conversion Factors

	Multiply	By	To obtain
Length	ft	0.3048	m
	$miles$	5280	ft
	$miles$	1609.344	m
	yd	0.9144	m
Area	ft^2	0.092903	m^2
	$acre$	4046.8564	m^2
	mi^2	2.589988 x 10^6	m^2
	$hectare$	$10,000$	m^2
Rate	$inches/yr$	2.2815 x 10^{-4}	ft/day
	$inches/yr$	6.9541 x 10^{-5}	m/day
	ft/day	0.3048	m/day
	gpd/ft^2	0.0407	m/day
Volume rate	ft^3/s	$2,446.5754$	m^3/day
	ft^3/s	86400	ft^3/day
	gal/min	5.4510	m^3/day
	gal/day	0.0038	m^3/day

Appendix B

Building W*h*AEM Base maps using the Internet

B.1 Getting USGS DLGs maps from the Web

W*h*AEM has utilities to convert the USGS digital line graph (DLG) maps into the binary base map format (BBM). The USGS DLGs are available for download on the Internet at their GeoData webpage. Point your web browser to edcwww.cr.usgs.gov/doc/edchome/ndcdb/ndcdb.html. Figure B.1.

The DLG maps are available at two scales: 7.5 minute (or 1:24,000) and 30 x 60 minute (or 1:100,000). The 30 x 60 minute maps are stored in optional format, while the 7.5 minute maps are stored in the new Spatial Data Transfer Standard (SDTS) format. Complete coverage is available of the USA at the 30 x 60 minute scale. While coverage at the 7.5 minute scale is not complete, you can check the status of maps for your state by going to the web page mcmcweb.er.usgs.gov/status/dlg_stat.html.

We will demonstrate the capability for downloading the 30 x 60 minute hydrography base map for Vincennes, Indiana.

You can select the DLG maps by alphabetical List, by State, or by Graphics. If you select by Graphics, you will be presented with a map of the USA. Locate your mouse and click on the point on the map near west-central Indiana that you want to zoom in to. Figure B.2.

The DLG maps are stored in files associated with their location and category, and the name reflects this information. The 1:100,000 scale quad in divided in eight 15-minute quads. Table B.1. Each of these quads contains the DLG for the associated category: hypsography, hydrography, roads, railroads, and miscellaneous. Table B.2. Therefore, the hydrography quad for Vincennes, IN, is **VI1HYF06**, which refers to the sixth quadrant (**F06**) of the Vincennes 1:100,000 map (**VI1**), containing hydrography (**HY**). Now select the Vincennes 30 x 60 minute map with your mouse. Figure B.3

Table B.1:

F01	F02	F03	F04
F05	F06	F07	F08

The 30 x 60 minute Vincennes map is stored in two locations on the server. Select the Vincennes west link that contains the sixth quadrant. Now select the hydrography link. Select the file `VI.HYF06.opt.gz`. Save the file to your project workspace on your hard disk.

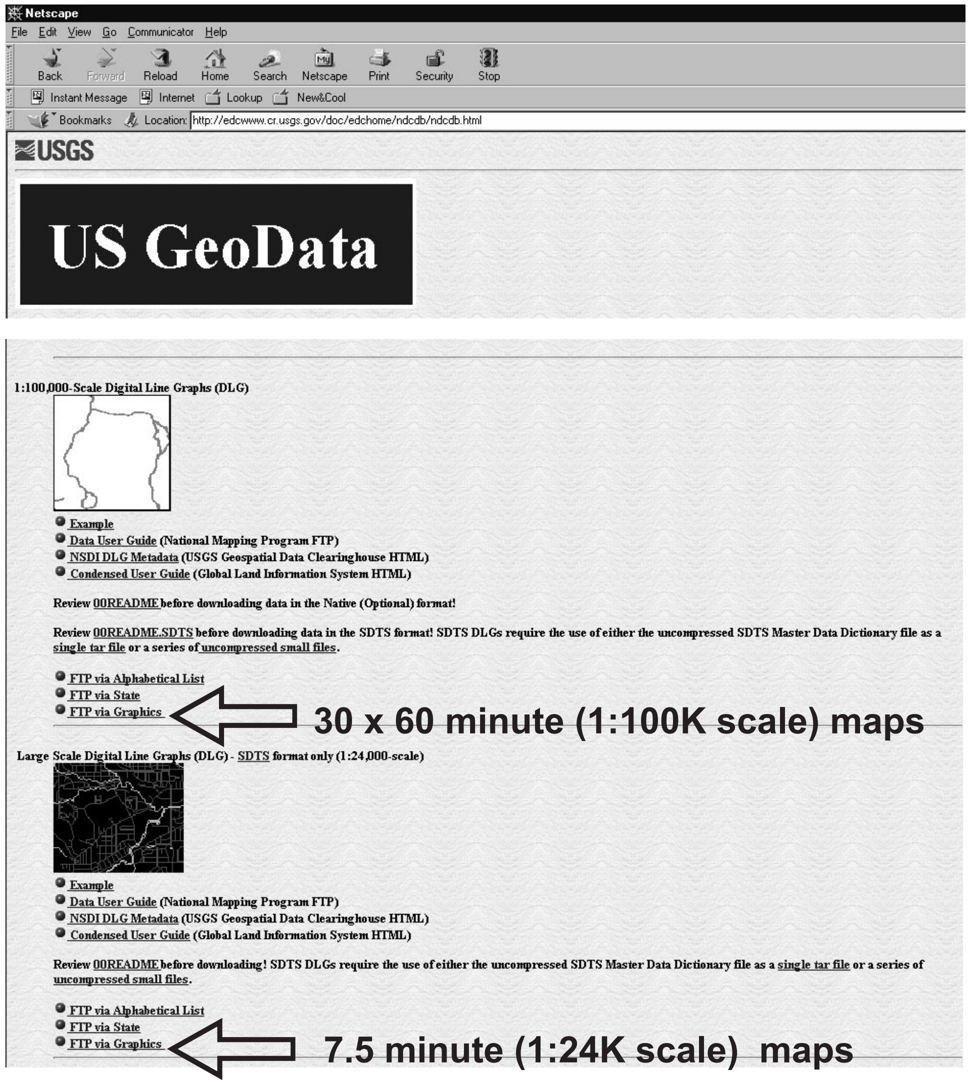


Figure B.1:

B.2 W*h*AEM DLG to BBM Utility

From the W*h*AEM menu, select **Tools** , and then **Convert DLG to Basemap**. Select the compressed file you downloaded from the Internet; for our example, `VI.HYF06.opt.gz`. W*h*AEM will automatically call the utility gzunzip, and then the utility chop. You will need to close the DOS box by clicking the X in the upper right corner when the message reports the utility is finished in the top (blue) message line. Finally, the utility will do the conversion from DLG to BBM, and store the file in your workspace. You can now use this BBM in a new database, or add it to an existing project with the **Project** , **Base Map Settings**, **Add BBM** sequence.

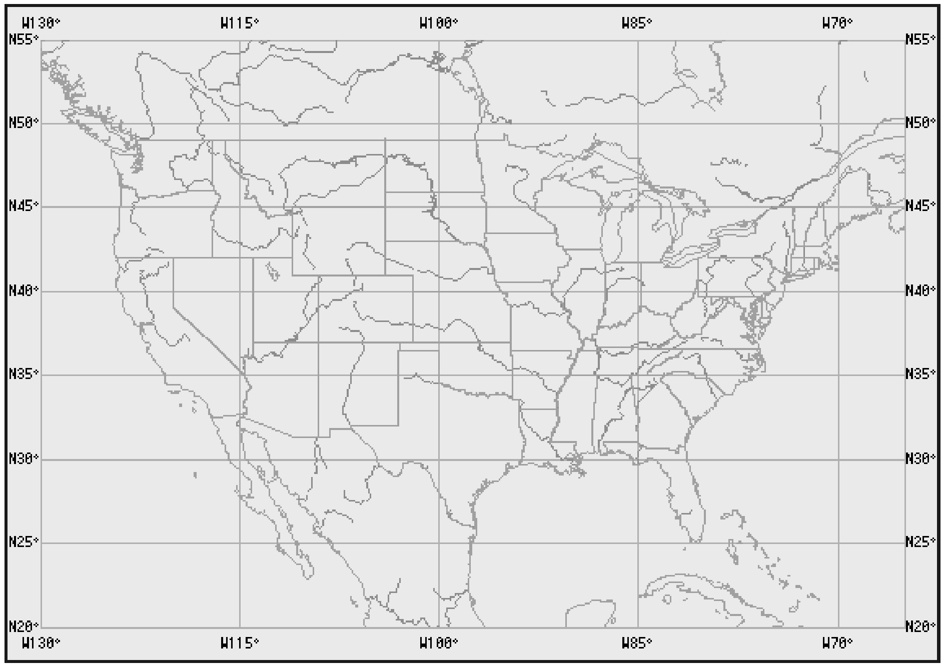


Figure B.2:

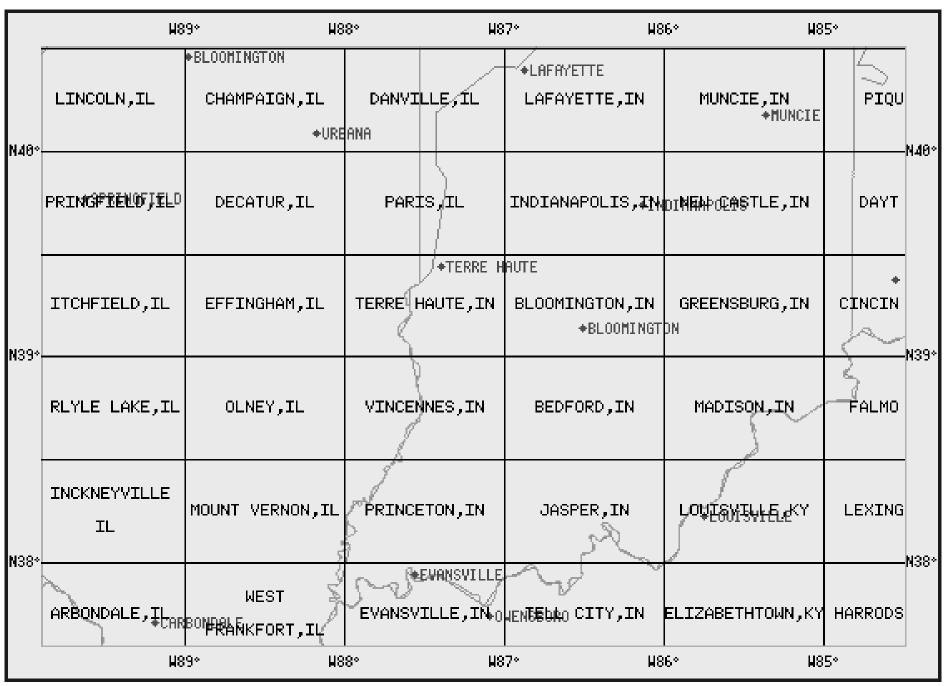


Figure B.3: Select Vincennes, IN map.

Table B.2:

Category Name	Abbreviation
hypsography	hp
hydrography	hy
boundaries	bd
roads and trails	rd
railroads	rr
miscellaneous transportation	mt

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